PROBLEMS OF PARACHUTE TECHNOLOGY

H. Blenk, C. Saliaris, H.G. Heinrich, G. Bünger,
K. Lorke, and H.-J. Klewe

(NASA-TT-F-16139) PROBLEMS OF PARACHUTE TECHNOLOGY (Kanner (Leo) Associates) 84 p HC $4.75 CSCL 01C

N75-16508

Unclas
G3/02 09680

Translation of "Probleme der Fallschirmtechnik," Deutsche Forschunganstalt für Luft- und Raumfahrt, Brunswick, West Germany, Institut für Flugmechanik (Proceedings of the Institut für Flugmechanik Symposium on Parachute Technology, Brunswick), 15 Feb. 1967, Report DLR-MITT-67-22, 108 pp

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 FEBRUARY 1975

STANDARD TITLE PAGE

1. Report No. NASA TT F-16,139	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PROBLEMS OF PARACHUTE TECHNOLOGY		5. Report Date February 1975
		6. Performing Organization Code
7. Author(s) H. Blenk, C. Saliaris, H.G. Heinrich, G. Bünger, K. Lorke, and H.-J. Klewe		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Leo Kanner Associates Redwood City, California 94063		11. Contract or Grant No. NASw-2481
		13. Type of Report and Period Covered Transltion
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "Probleme der Fallschirmtechnik," Deutsche Forschunganstalt für Luft- und Raumfahrt, Brunswick, West Germany, Institut für Flugmechanik (Proceedings of the Institut für Flugmechanik Symposium on Parachute Technology, Brunswick), 15 Feb. 1967, Report DLR-MITT-67-22, 108 pp

16. Abstract

Symposium papers on parachute techniques with emphasis on stress distribution in the parachute canopy, stabilization problems, steerable parachutes, cloths, ribbons and cords for parachutes, measuring techniques, and parachutes and recovery systems in the supersonic range are presented.

17. Key Words (Selected by Author(s))	18. Distribution Statement Unclassified-Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 84	22. Price

NASA-HQ

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K. Lorke, and H.-J. Klewe

OPENING REMARKS (H. Blenk) /7*

Ladies and gentlemen!

On behalf of the German Research Laboratory for Aeronautics and Astronautics, I would like to welcome you to this Symposium of the Institute for Flight Mechanics on Problems of Parachute Technology, and thank you for the interest which you have expressed by your presence here. We had not anticipated that the interest would be so large because the field of parachutes is after all a rather specialized one. This is all the more reason for us to be pleased at the active participation of all of you who believe you can contribute something to this topic or who hope to profit from this symposium.

We will try to keep the scheduled reports short, to allow as much time as possible for discussion. I hope that we will have useful talks after the reports are given. Later on, we may publish a report on this symposium, so that others can read who said what and in which direction the interest lay.

I would like to say a few words about the subject itself. In 1953, we resumed work in here in Braunschweig at the Institute for Flight Mechanics of the DFL, and organized an initially very small Parachute Division, since we intended to deal with testing problems in the field of parachutes as well. The Director of this division was Mr. Heins, who later transferred to the Federal Ministry of Defense, where he is still active in his old field. In 1963, Mr. Melzig took over the division; it was expanded so that /8 it now includes about 40 people, a generous number for such a special area. Support from the Federal Ministry of Defense through the granting of additional contracts has been particularly valuable to us.

I should mention a second point, however, and that is American cooperation, which has been of great assistance. As most of you known, parachute research was begun in 1938 at the "Graf Zeppelin" Research Institue in Stuttgart under the direction of Prof. Georg Madelung. At the end of the Second World War, Germany had a great lead on other countries in the development of stable

* Numbers in the margin indicate pagination in the foreign text.

parachutes. Prof. Heinrich, who is with us today, was working for Prof. Madelung in that research institute at that time, and he has continued to work in the same field for many years in the USA. As aeronautics research revived here in Germany, he contacted us, and since then this contact has become closer and closer. With his aid, for example, we were on two occasions able to devote an entire day to parachute problems at the annual meetings of the Scientific Society for Aeronautics (1959 in Hamburg and 1964 in Berlin). Along with Prof. Heinrich, we are also in contact with another former Stuttgart worker, presently in the USA, namely R.J. Berndt, now working on parachutes for the U.S. Air Force in Dayton, Ohio. From both these American sources, we have received much assistance, for which we are very grateful.

The cooperation between Germany and America is often portrayed as trading an elephant for a rooster. What we have to offer is the rooster, and what we receive is the elephant. It is understandable that the Americans are not exactly pleased about this situation. Naturally, we hope that this does not remain the case, and improvements can be recognized in many areas.

Melzig, the Director of our Parachute Division, has been in /9
the USA for the past half year, in a way occupying the chair of Prof. Heinrich, and giving lectures at the University of Minnesota, while Prof. Heinrich is in Germany, giving lectures at Stuttgart Technical University, and working with us at the Institute for Aeronautics of the DFL in Braunschweig. This exchange of people is what I believe to be the best method of cooperation. It is practically impossible to write down and exchange everything one knows; it is best for the people to change places; the ideas then go along, are exchanged and refined, bringing about real cooperation. As for our relationship with American agencies, we hope that an agreement will be concluded in the near future between the Federal Ministry of Defense and the Pentagon, providing for joint work on a major research project in the area of parachutes; our part will involve the construction of a quite expensive test facility. Hence, ladies and gentlemen, you can see that the acorn planted in 1953 has in the meantime turned into quite a nice tree, and we hope it will continue to grow in the future.

I must bring up one further point, namely the connection between research and industry. It is evident that research cannot surmount all problems by itself. We require the collaboration of industry. They can give us valuable stimuli from practical experience. I therefore am very pleased to see representatives of the parachute companies at our symposium, and hope that today's discussions will assist in strengthening existing ties.

STRESS DISTRIBUTION IN THE PARACHUTE CANOPY (C. Saliaris) /10

Summary

The following short report is intended as a contribution on the problem of "stress distribution in the parachute canopy." A method of stress analysis using pressure distribution measurements will be outlined.

Results are presented on the distribution of circumferential stresses in the steady-state case for planar round-canopy and hemispherical parachutes.

Reference is also made to problems in direct stress measurements.

1. Introduction /11

In selecting the mechanical characteristics of parachutes, it is important to know how stresses vary in space and time. Any determination of stresses is still beset with great difficulties. No direct stress measurements have yet been made on parachute canopies. The first attempt at a mathematical analysis was made in 1923 by R. Jones in England. This was followed by a number of other tries, all restricted to the steady-state case of a fully deployed parachute. Studies with this restriction, however, are not suitable as a basis for calculating the strength of a parachute, since the dynamic forces acting during the unsteady filling phase exceed the static forces in the steady state by a considerable amount. Substantial progress was achieved in a report of H.G. Heinrich and L.R. Jamison [1] which appeared recently, in which an analytical method was developed for calculating the stresses in a parachute canopy during all phases of parachute deployment. Drawing on experimentally determined pressure distributions and canopy profiles, one can calculate the stresses with this method. The method is general and can be applied to any type of parachute as long as its geometry is known.

2. Parachute Geometry and Stresses

Fig. 1-4 are presented to assist in general comprehension. The first step in the stress analysis is to determine the canopy profile along a chord and along the gore bisector. In order to calculate the stresses, the pressure distribution associated with each canopy profile is also required. This distribution is measured in wind-tunnel or free-flight tests. For this purpose, we have developed a special pressure sensor, with which we have been able to record differential pressures in parachute canopies as functions of time.

In the calculation, the following simplifying assumptions had been made: /12

1. At all times during deployment and in the steady-state case, the pressure load is constant in the circumferential direction and changes only in the meridian direction.

2. For a trajectory element, the membrane equation applies:

$$\Delta p = \frac{f_1}{r_b} + \frac{f_2}{\rho} \tag{1}$$

since $\rho >> r_b$, only the tangential stress f_1 is considered.

3. Because of the uniform pressure distribution, the material between two adjacent chords forms a circular arc.

4. Stresses which might be induced by inertial forces are neglected.

As the parachute opens, its lateral profile is photographed from the ground on high-speed film, and from it the profile of the gore bisector is determined. From the relationship between this profile and the gore geometry, the profile along a chord can be calculated by first determining the distance b_0 between the chord and the gore bisector. The mathematical derivation will not be given here.

Asterisked variables have been normalized by dividing by half the nominal canopy diameter $D_0/2$. Let N be the number of gores.

Then

$$b_o^* = \frac{1}{4} \tan \frac{\pi}{N} \left[6 \left(1 - \frac{X_c^*}{S_g^*} \right) \right]^{\frac{1}{2}} (S_g^* + X_c^*) \tag{2}$$

$$X_c^* = X_g^* - b_o^* \sin \Phi , \tag{3}$$ /13

as long as the material between two adjacent chords forms a circular arc, which is smaller than a semicircle; furthermore

$$b_o^* = \tan \frac{\pi}{N} \frac{S_g^* + (1 - \frac{\pi}{2}) X_g^*}{1 + \tan \frac{\pi}{N} (1 - \frac{\pi}{2}) \sin \Phi} , \tag{4}$$

when the material forms a semicircle or a semicircle with parallel extensions.

The equation used to determine b_δ^* depends on the magnitude of the expression:

$$A = \frac{\frac{2S_r^*}{\pi}\left[1 + \tan\frac{\pi}{N}\sin\Phi\left(1 - \frac{\pi}{2}\right)\right]}{X_g^* - \sin\Phi\tan\frac{\pi}{N}S_g^*} \tag{5}$$

if $A < 1$, Equations (2) and (3) are employed, while Equation (4) is selected if $A \geq 1$.

Hence, the entire geometry of the canopy is known, and one can now compute the stress distribution. Applying the membrane equation yields the tangential stress as a function of the gore curvature and of the differential pressure:

$$f_1 = \Delta p \cdot r_b \; . \tag{6}$$

With the aid of this equation and the known geometry of the canopy, and supposing that the Hooke's law of elasticity applies, we obtain the following general dimensionless equation for the strain ε:

$$\varepsilon^3 + \frac{6\left(1 - \frac{X_c^*}{S_g^*}\right) - 3(\lambda^* S_g^*)^2}{6 - (\lambda^* S_g^*)^2}\varepsilon^2 - \frac{3(\lambda^* S_g^*)^2}{6 - (\lambda^* S_g^*)^2}\varepsilon - \frac{(\lambda^* S_g^*)^2}{6 - (\lambda^* S_g^*)^2} = 0 \, , \tag{7}$$

where /14

$$\lambda^* = \Delta p \frac{D_o/2}{E} \tan\frac{\pi}{N} \tag{8}$$

When the material between two adjacent shroud lines forms a semicircle, we have

$$\varepsilon = \lambda^* X_c^* \; . \tag{9}$$

The cubic equation for ε is solved by iteration, using $\lambda^* X_c^*$ as the first approximation. The stress analysis shows that the stresses in a single type of parachute can be reduced by increasing the number of gores.

The diagram (Fig. 5) shows the results of such a stress analysis in the steady-state case for the round-canopy and hemispherical parachutes. The stress is plotted along a chord from the top to the bottom. The round-canopy parachute has 28 gores and a nominal diameter of 28 ft (8.53 m); it was supplied by Brüggemann & Brand.

The hemispherical parachute has 30 gores, and a nominal diameter of 9.25 m; it was prepared at the Flight Mechanics Institute of the DFL. Both parachutes were dropped from an elevation of 300 m at a speed of about 200 km/hour. A weight of 100 kg was suspended from the parachute. The modulus of elasticity of the fabric was determined by tensile tests; it was 3244 kg/m. The fabric was nylon MIL-C-7020 D, Type I, 1.1 oz/yd^2, with a tensile strength of σ_B = 700 kg/m.

The pressure distribution on which the calculation is based was obtained from wind-tunnel measurements, and measured with pressure sensors developed in the Parachute Division. This distribution is depicted in Figs. 6 and 7.

An examination of the diagrams shows that the hemispherical parachute is subject to higher stresses, despite the smaller surface loading. Hence, as far as strength is concerned, the round-canopy parachute would be preferred over the hemispherical parachute. The calculated maximum stress of 3 kg/m in the steady-state case is a very small value, amounting to only about 0.4% of the tensile strength. /15

Of greater importance, therefore, are the much higher stresses during the opening phase, which are likewise to be determined with the aid of this method.

The method for ascertaining the nominal tensile strength consists of slowly applying a load to a fabric sample in the warp or woof direction in a static tensile test until the fabric parts. However, the actual loads during the opening of the parachute are applied with high speed and at high frequency. The dynamic tensile strength in relation to loading rate or vs. a large number of cycles is still unknown, since there are no appropriate testing machines.

3. Experiments to Measure Stresses in Parachute Fabrics

We are still in the initial stages of our experiments, so that nothing essential can be reported in the way of results.

We first attempted to measure the stresses with the aid of a steel measuring element with pasted-on strain gauges. Two models were tried out and a third is under consideration (Fig. 8). Calibration curves have been determined through tensile tests for the first two models.

Then the measurement elements were glued to wider cloth samples of various lengths. In order to acquire usable results, the cloth was cut between the contacts of the strain gauge.

Assuming that the stresses on the connecting clamps were equal to those measured at the measuring point, it was found that the strain gauge registered too high a stress. /16

Furthermore, with long fabric samples, the reading was lower -- but still too large -- than for short samples of the same width.

These two undesirable effects can be explained by the following analysis:

The modulus of elasticity of the strain gauge is considerably larger than that of the fabric. One might almost say that the gauge does not stretch at all in comparison with the fabric. Therefore, the fabric to which the element is glued will stretch much more than the adjacent material, thus inducing the higher stresses at the measuring points.

Naturally, the results of such tensile tests cannot be applied without reservations, since the stresses on a parachute are applied on two axes. Tests in this direction remain to be conducted.

A second route, namely to calculate the stresses from the strains in the fabric, is likewise fraught with difficulties. First, it is difficult to find strain gauges which will stretch much more than the fabric. Second, calculating stresses from the strain is problematic, since textiles do not obey Hooke's law and furthermore because there is a hysteresis loop in the stress-strain diagram.

So far, the parachute strength problem has not been solved satisfactorily.

In conclusion, we mention the following complex of questions:

1. The assumption that the stresses in a gore element are mainly in the tangential direction can be made as soon as the fabric element has been filled out so that it is stiff and does not flutter. However, during fluttering, there are additional stresses such as those in a vibrating rope. They can reach the same order of magnitude as the tangential stresses. /17

Precisely when a parachute canopy tears is not known. It must be conjectured that tearing can occur even in the fluttering period, since maximum pressure differences were measured at this time.

2. The influence of the inertial forces induced by the masses of fabric on the stresses in the fabric must be investigated.

3. The dynamic tensile strength of the fabric in relation to the loading rate and to the number of cycles will also be investigated.

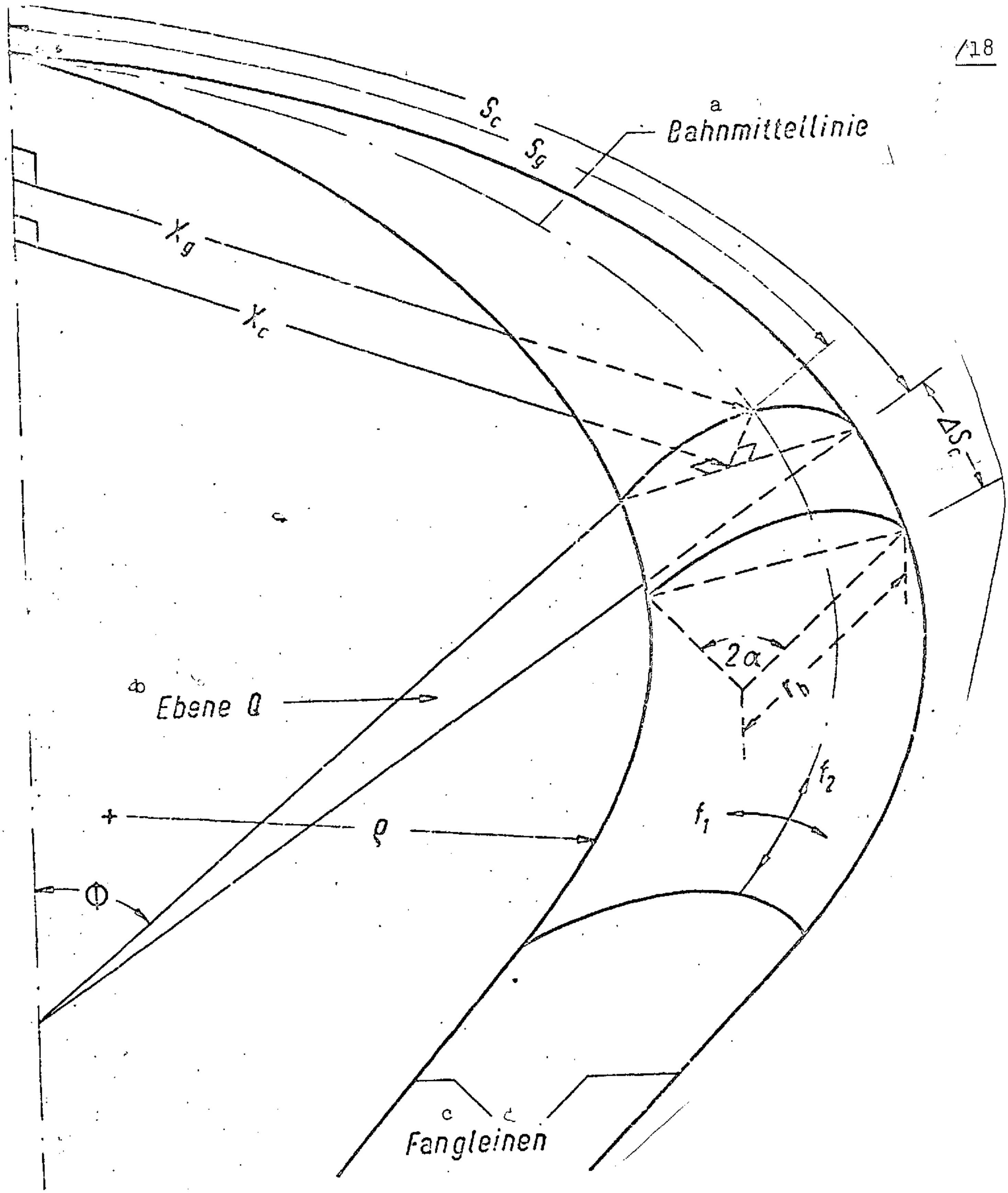


Fig. 1. Schematic of gore element.
Key: a. Gore bisector; b. Plane; c. Chords

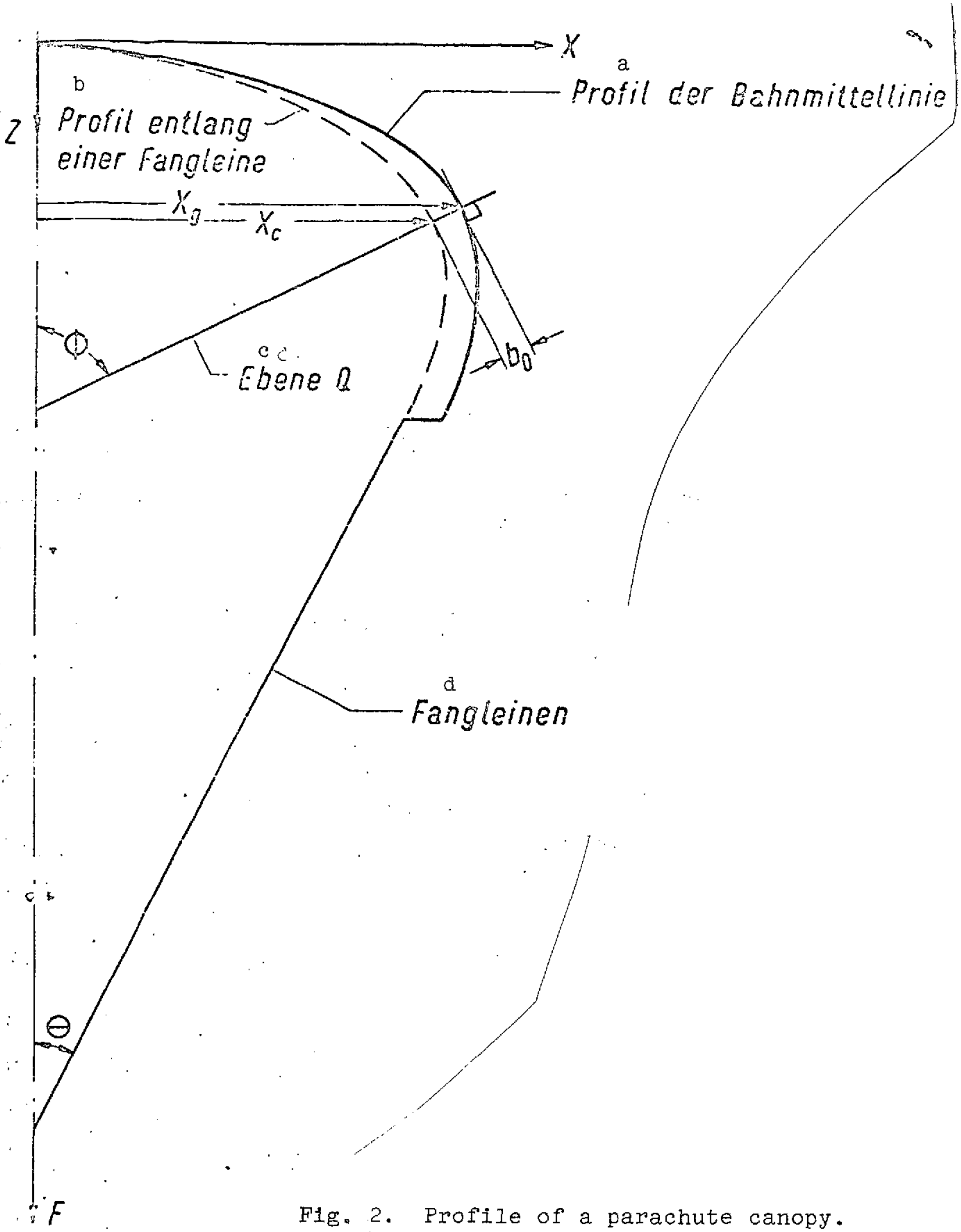


Fig. 2. Profile of a parachute canopy.

Key: a. Profile of gore bisector
b. Profile along chord
c. Plane
d. Chords

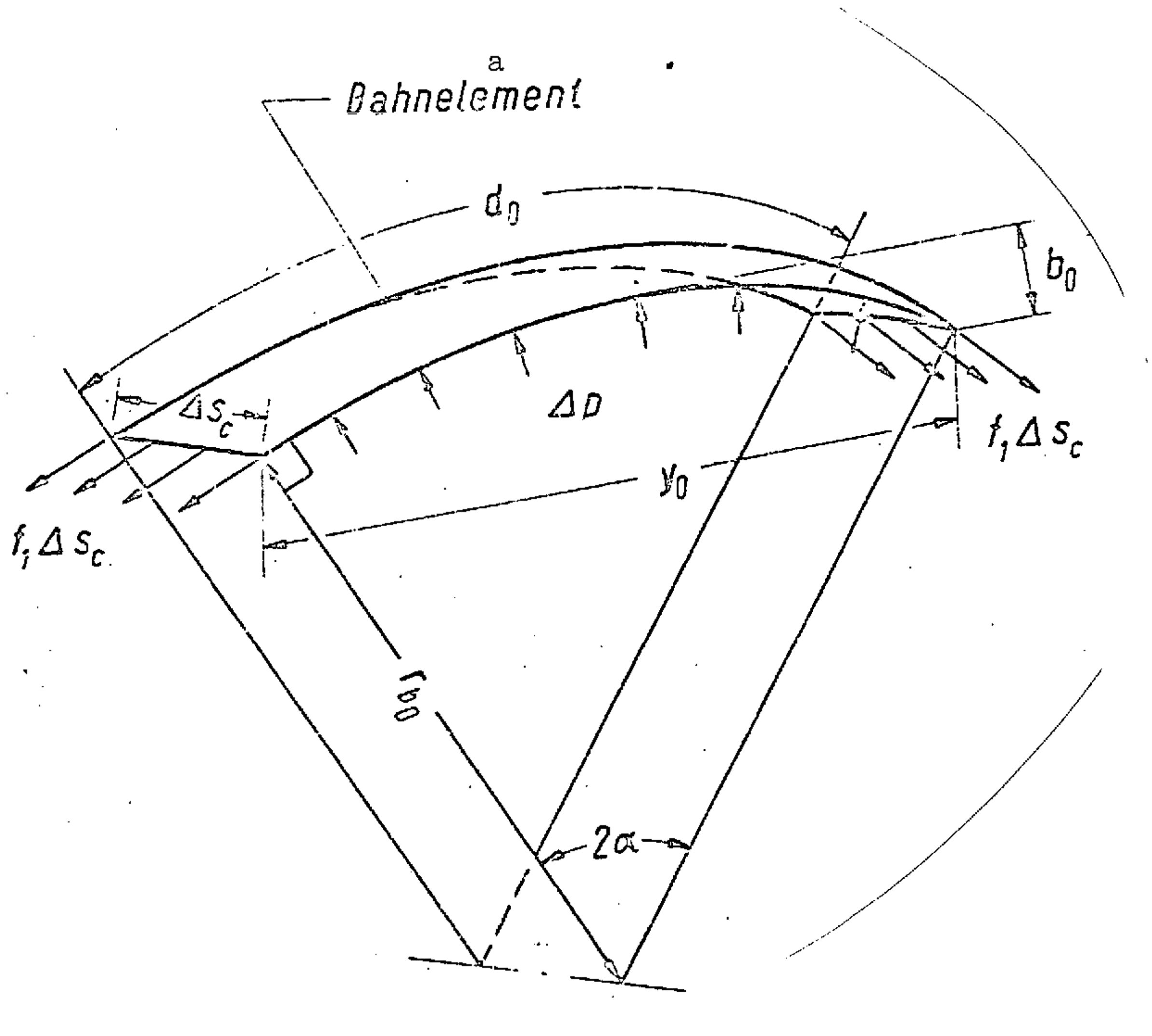


Fig. 3. Gore element with applied forces.

Key: a. Gore element

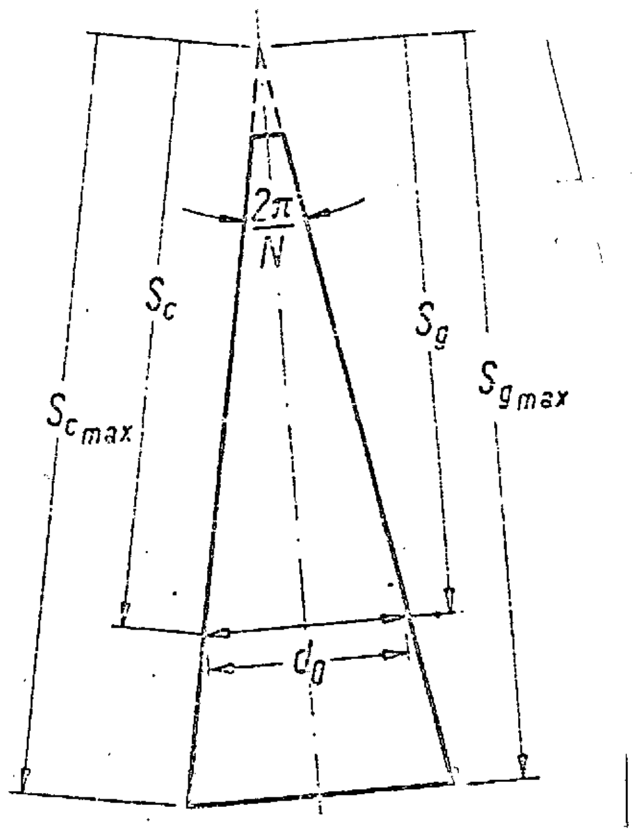


Fig. 4. Triangular gore sector of a planar round-canopy parachute.

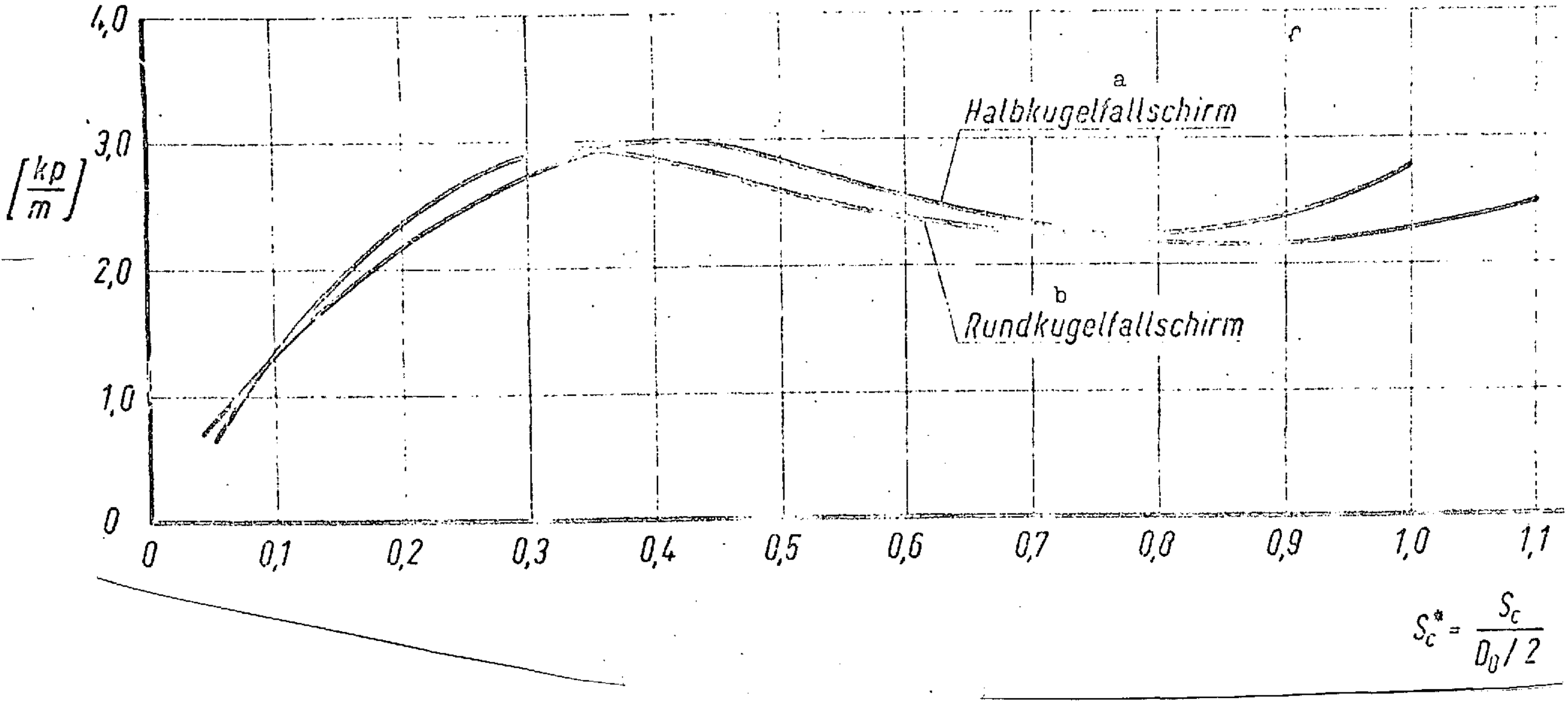


Fig. 5. Stress distribution along a chords on the canopy of the round-canopy and hemispherical parachutes.

Key: a. Hemispherical paracute
b. Round-canopy parachute
kp = kg

/2

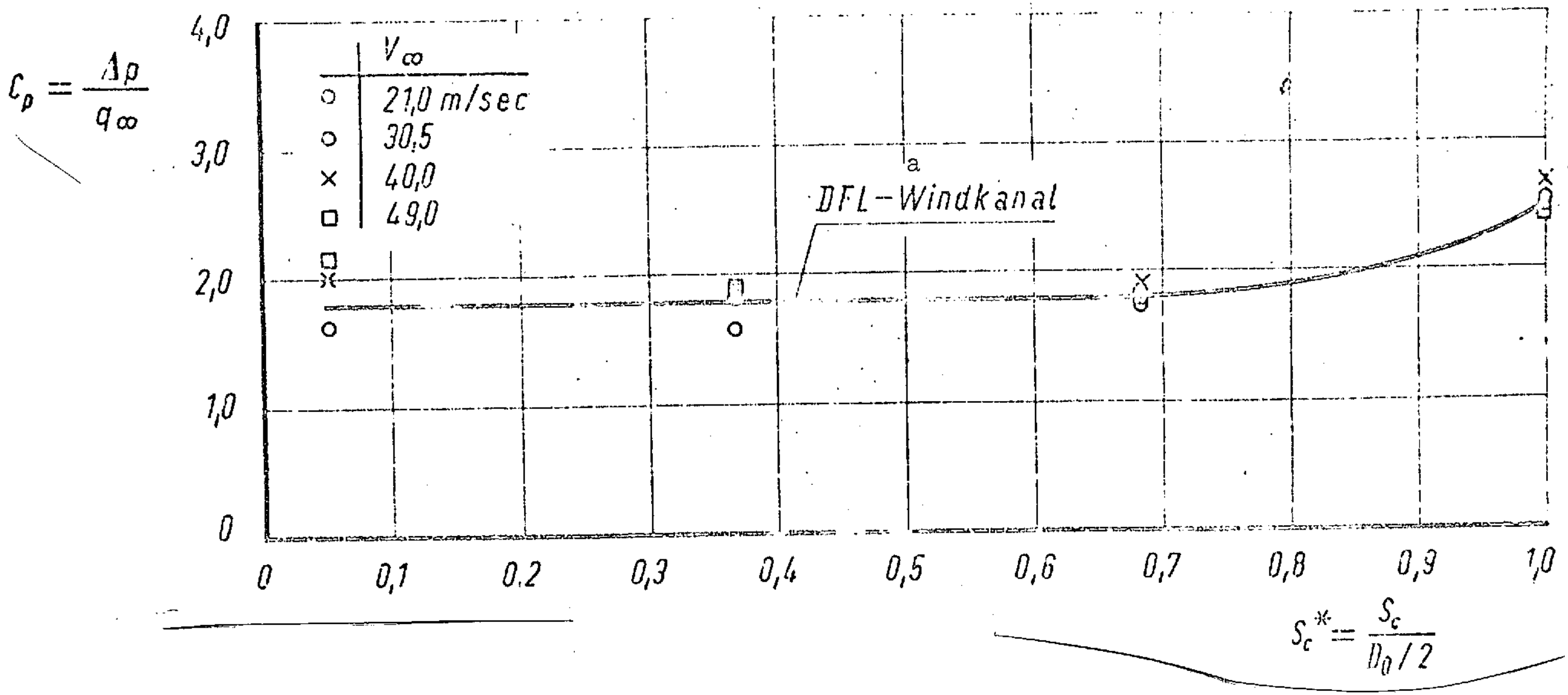


Fig. 6. Pressure distribution along a chord on the canopy of the planar round-canopy parachute from wind-tunnel measurements.

Key: a. Wind tunnel

/23

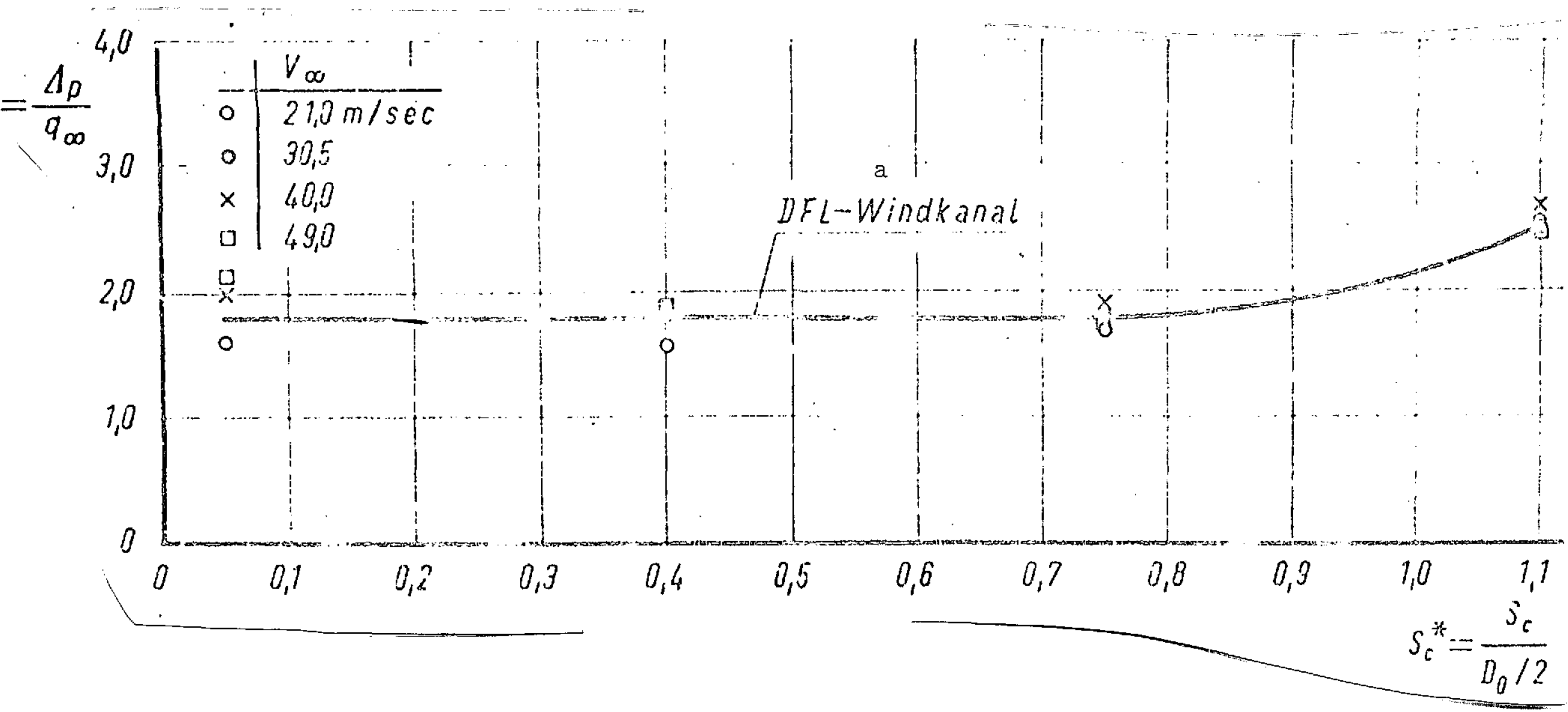
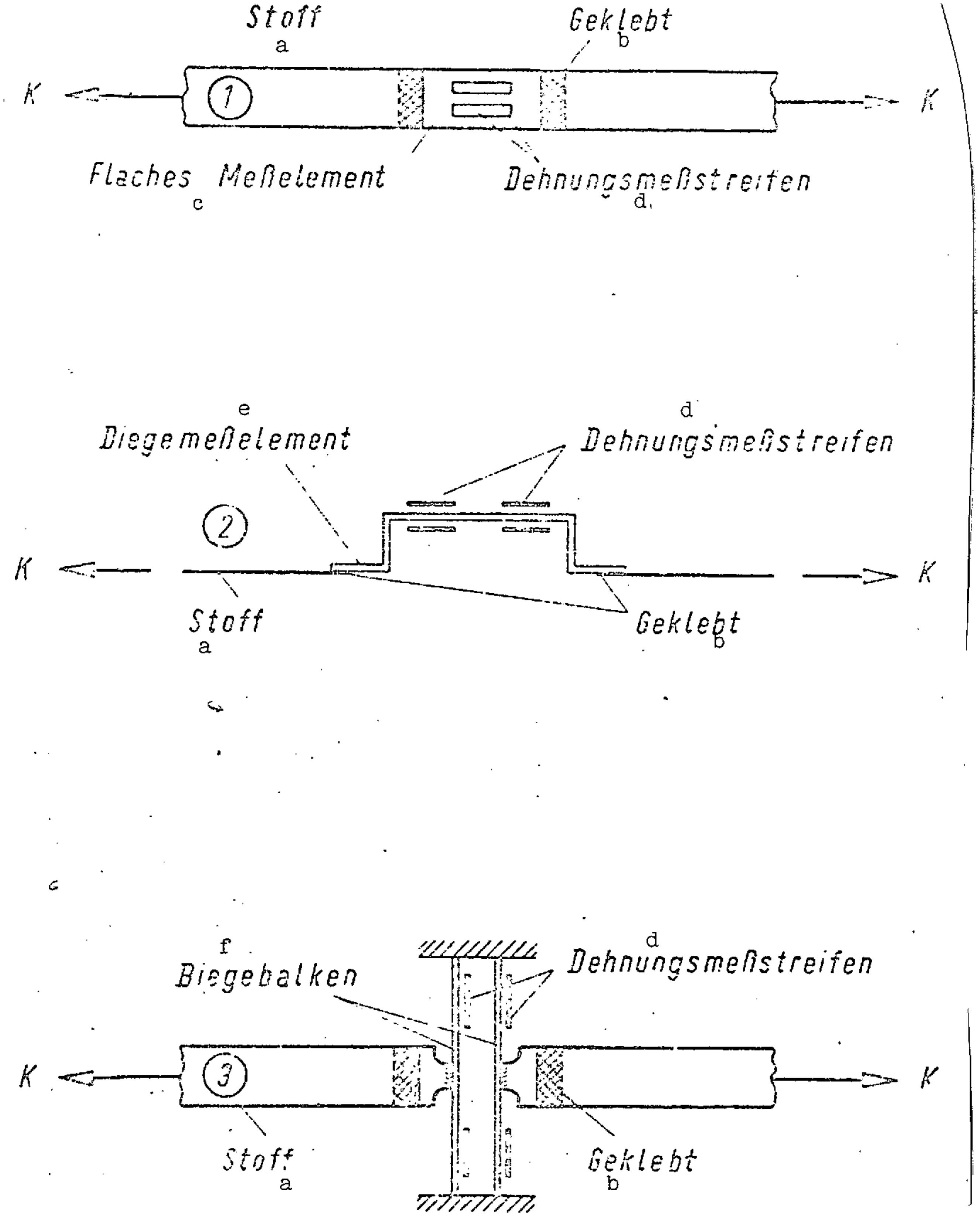


Fig. 7. Pressure distribution along a chord on the canopy of the planar hemispherical parachute from wind-tunnel measurements.

Key: a. Wind tunnel

/24



/25

Fig. 8. Schematic of stress measurements in parachute cloth.

Key: a. Cloth
b. Glued
c. Flat measurement element
d. Strain gauges
e. Bending measurement element
f. Transverse beams

REFERENCES

1. Heinrich, H.G. and Jamison, L.R., "Parachute stress analysis during inflation and at steady state," J. Aircraft 3, 52-58 (1966). /17

2. Melzig, H.-D. and Schmidt, P.-K., "Pressure distribution during parachute opening. Phase I: Infinite [illegible] operating case," Technical Report AFFDL-TR-66-10, 1966.

Kircher: In the calculation, it was assumed that the fabric forms a circular arc between two adjacent cords. Is this assumption realistic?

Saliaris: If it is assumed that there is a constant pressure distribution in the tangential direction, it can be shown that the result will be a circular arc. American authors have made other assumptions and then arrived at elliptical integrals. However, no one knows whether that is more accurate.

Kircher: On drogues, there are frequently forces causing a distortion of the fabric along the cord. Perhaps it would be a good idea to find ways to sew the parachute better, in order to avoid stress peaks which might result in rips at the seams.

Azmeh: Have you measured the pressure distribution on the circumference as well?

Saliaris: No, but in the steady-state case, one can assume a constant pressure distribution in the tangential direction if the parachute is symmetrical.

Azmeh: Have you ever attempted to employ optical methods to measure the stresses?

Saliaris: We considered the idea. However, when the cloth flutters, there does not appear to be any good way of measuring the stresses with an optical method. /27

Bünger: What does the stress distribution in the circumferential direction look like near the edge? In this region, the forces must be diverted onto the cord, and therefore must act in the meridian direction. In that case, is the assumption that the stress in the meridian direction can be neglected still valid near the edge?

Heinrich: If you look at a real parachute, you will see that the fabric is always loose and limp between the two cords at the edge. Therefore, there are certainly no longitudinal stresses near the edge.

In the Kostelezky parachute, on the other hand, which is essentially a ribbon parachute in which the ribbons run from one edge over the top to the other edge, the longitudinal force is taken up by these ribbons at the edge. Therefore, in the Kostelezky parachute, we certainly have stresses in the longitudinal direction, but these ribbons are quite different from those in a normal parachute. In a normal ribbon parachute or round-canopy parachute, I cannot imagine any way for large longitudinal stresses to appear. On the other hand, the parachutes are designed so that the threads do not travel in precisely a circular direction, but rather at an angle of 45°. This so-called diagonal construction naturally gives rise to stresses at a 45° angle, so that the assumption that only radial stresses are present is a simplification, but probably not a very bad one. The prevalent view in the /28 USA is that the longitudinal stresses in the canopy must be negligibly small.

Furthermore, a type of sphere always forms when the parachute opens. While this sphere is forming, the cords are still the weight-bearing elements; between them, the fabric bulges in one fashion or another. Wind-tunnel measurements have shown that the pressure distribution on the canopy is relatively uniform while this sphere is forming. Under this assumption, it can be proved that the "bulges" of the fabric must be circular.

Finally, we should say a word about the "stress balance canopy," which was developed after this theory had been formulated. As can be shown, the stress is a minimum when the circular arc is a complete semicircle. For this reason, parachutes were manufactured in which the gores were no longer triangular, but curved. There were curves along the side, so that the parachute always had enough fabric, once it had opened, in order to form a semicircle. Such a parachute has the smallest possible radii, and, accordingly, the smallest possible stresses. Unfortunately, these parachutes do not open symmetrically. They do have enough material to form semicircle everywhere, but they acquired many folds, so that this semicircle construction was abandoned.

By now, very successful parachutes have been made in which the angle enclosed by the circular arc is 135°. These parachutes are very light and can be dropped at high speed. In this design, /29 fabric is added at the top, where it will not increase the weight very much, and cloth is removed near the edge, where it is not needed. This saves a great deal, without giving rise to large additional stresses. Hence, the cloth is exploited better. These parachute canopies have been named "stress balance canopies." This is an application of the simplified theory.

STABILIZATION PROBLEMS (Helmut G. Heinrich, University of Minnesota, currently visiting the German Research Laboratory for Aeronautics and Astronautics in Braunschwig) /30

1. Introduction /31

The question of parachute stability was actually the external stimulus for working on improving parachutes in Germany. In 1927, H. Doetsch of the DVL published a work describing studies on all possible parachute canopies in a wind tunnel, with the object of determining the aerodynamic properties of parachutes. This brought a certain organization into thinking in Germany, and the concepts "stable" and "unstable" were developed. These concepts were never defined very clearly and certainly have never been used very clearly. We will now show how stability is defined in the U.S. and how this stability principle can be applied to various aerodynamic objects.

The analysis will be restricted mainly to statistical stability for parachutes. From aircraft theory, we have the ideas of lift, drag and moment, i.e. tangential force, normal force, and moment.

2. Definition of Stability for Parachutes

For a parachute with a relative airspeed of V at an angle α, we can define the tangential force, normal force and moment as in Fig. 1:

$$T = c_T \frac{\rho}{2} V^2 S,$$

$$N = c_N \frac{\rho}{2} V^2 S,$$

$$M = c_M \frac{\rho}{2} V^2 S\, D$$

(D = diameter, S = area, ρ = density of air) where T is in the direction of the axis of symmetry of the parachute, N is normal to it, and M is a right-handed positive moment. The qualitative dependence of the coefficients c_T, c_N, and c_M on α can be seen from Fig. 2 and 3. Static stability means that $dc_M/d\alpha < 0$. In /32
Fig. 2, we have a parachute statically stable about $\alpha_{St} = 0°$; in Fig. 3, the parachute is statically unstable about $\alpha = 0°$, but stable about $\alpha_{St} = \alpha_1$. In Figs. 4a and 4b, the two cases are illustrated once more. Fig. 4a shows a parachute stable about $\alpha_{St} = 0°$. Fig. 4b shows a parachute stable about roughly $\alpha_{St} = 20°$.

In the first case, we acquire a vertical motion, and in the second case, slip, oscillation, spin, etc. about the center of gravity. However, a falling parachute is subject to the dynamic stability conditions as well, so that a single type of parachute may vibrate severely in one case and slip in another. These things can be calculated, and it is known that static stability about a given angle of attack is always a prerequisite for dynamic stability. If e.g. dynamic stability about a 0° angle of attack is desired, the parachute must have static stability for 0°. We will now discuss some special cases regarding these criteria.

3. Examples of Stabilizing Flying Objects with the Aid of Parachutes

If we wish to use parachutes for the purpose of stabilization, we must specify the stability problems involved. There will certainly be problems in which our main objective is to stabilize and to produce as little braking as possible. For instance, recall the German 1000-kg bomb, which had a diameter of 62 cm and which was stabilized with an 80-cm parachute. The terminal velocity of the bomb was 180 m/sec, and the bomb swung through about ±2°. The advantage of this parachute stabilization for the 1000-kg bomb was that the tail, amounting to about 40% of the entire length of the bomb, was eliminated, so that the bombs became quite a bit shorter. Because of its excellent stability, the bomb could be dropped with great accuracy.

A second very important application of stabilizing parachutes is encountered with air torpedoes, which are dropped from a low elevation in high-speed flight. The difficulties were that the torpedoes, which impact with the water at a very small angle, skip like stones along the water. Thus, an unbraked torpedo might /33
even strike the aircraft which released it. Therefore, before the war, and perhaps even at the end of the First World War, there were attempts to brake and stabilize torpedoes with parachutes. These experiments were unsuccessful, because the parachutes available at that time were unstable up to 20°. However, once highly stable parachutes were invented, Germany developed the L 30 air torpedo, which could be dropped at high speeds from a height of 50 m. German torpedo airplanes were equipped with these weapons at the time. The 100-kg torpedo was stabilized and braked with a 2-m parachute, in order to have an optimum combination of trajectory angle and velocity at the moment of impact. The final velocity of this torpedo was on the order of 100 m/sec, so that the problem was a combined stabilizing and braking one.

The next stability problems are mixed problems. For instance, it became necessary to have the capability of dropping a man rapidly from 100,000 ft to 20,000 ft, where his large parachute would open and bring him slowly down to Earth. An inexperienced person, falling for a long time without stabilization, usually begins to spin, a motion which can be so violent that physical injury can be anticipated from the centrifugal acceleration. Therefore, for this case, a parachute system was developed in which the man was stabilized between 100,000 and 20,000 ft by a 6-ft stabilizing chute. Upon disengagement, it drew out the main parachute. The degree of stabilization was not very great in this case. Swinging up to about 10° was not suppressed.

A further application of stabilization is found in space capsules. The one-man Mercury capsule was e.g. stabilized with a 6-ft ribbon chute. The two-man Gemini capsule weighs about 4750 lb and is stabilized in the first phase with an 8-ft ribbon parachute. For the second stage of these recovery systems, a mutation of the ribbon chute, namely a ring slot parachute, is used. This parachute is first reefed, and then opens completely. The parachute, both when reefed and when fully open, is also a /34
stabilizing parachute to some extent, with a stable position of about 10°.

Another practical problem in stabilization involves targeted supply tanks. The latter were first built and tested around the end of the war. They are dropped like bombs with a targeting device. Above the ground, a small chute is released which then pulls out a large one. This technique is well developed. We should also mention aircraft landing and drag chutes, the technology of which is known and well developed.

Finally, supersonic problems have appeared recently as in e.g. the recovery of space capsules. However, stabilization requirements for advanced spaceflight include high Mach numbers and NASA is interested currently in parachutes for velocity ranges around the Mach numbers of 5, 10 and 15. For the time being, however, these requirements will probably not be encountered except in spaceflight.

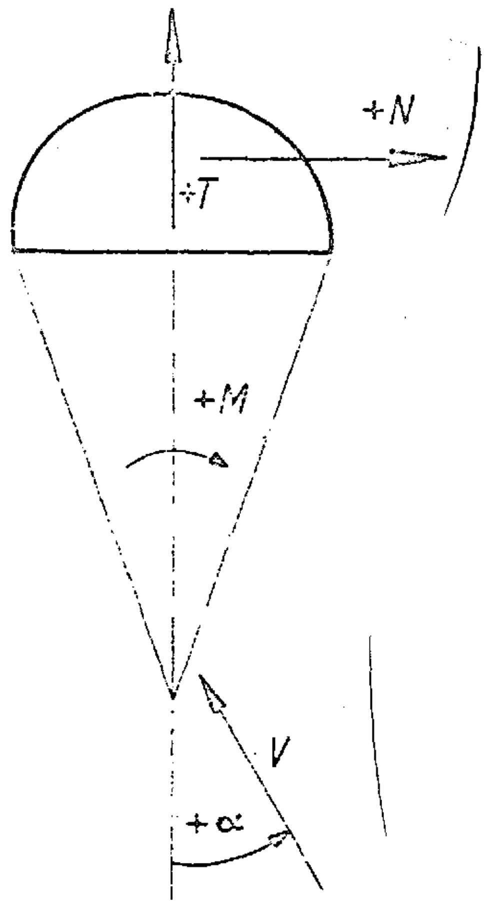


Fig. 1. Forces and moment on parachute.

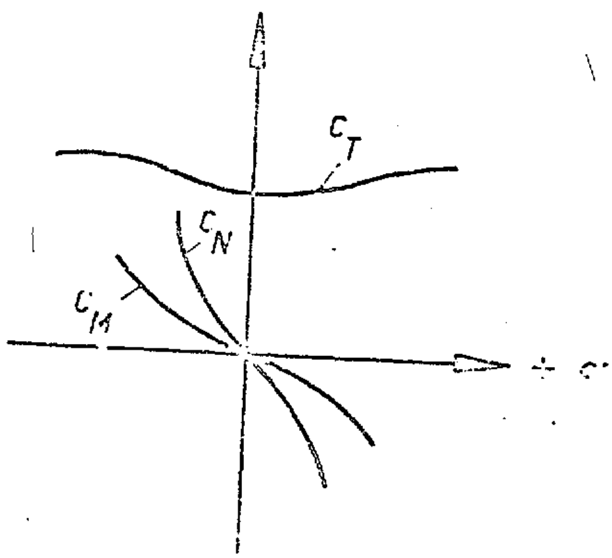


Fig. 2. Coefficient c_T, c_N and c_M in relation to angle α of attack (α_{stable} = 0°).

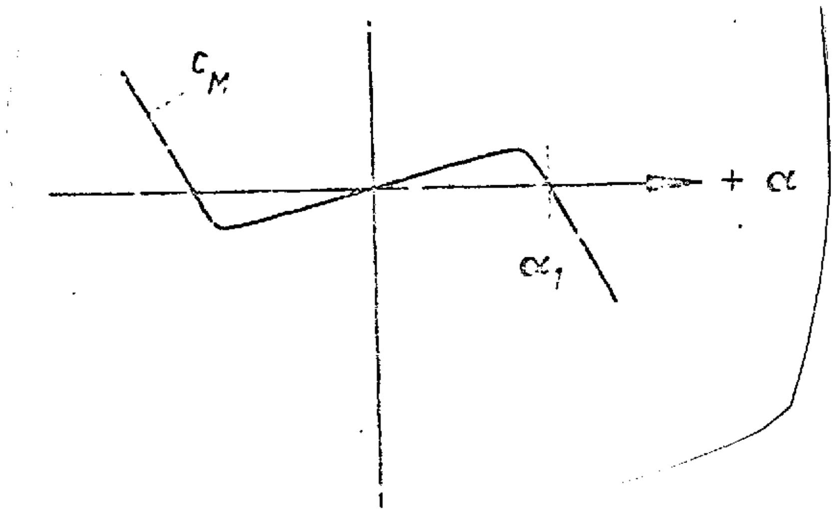


Fig. 3. Coefficient c_M as a function of angle α of attack ($\alpha_{stable} = \alpha_1$).

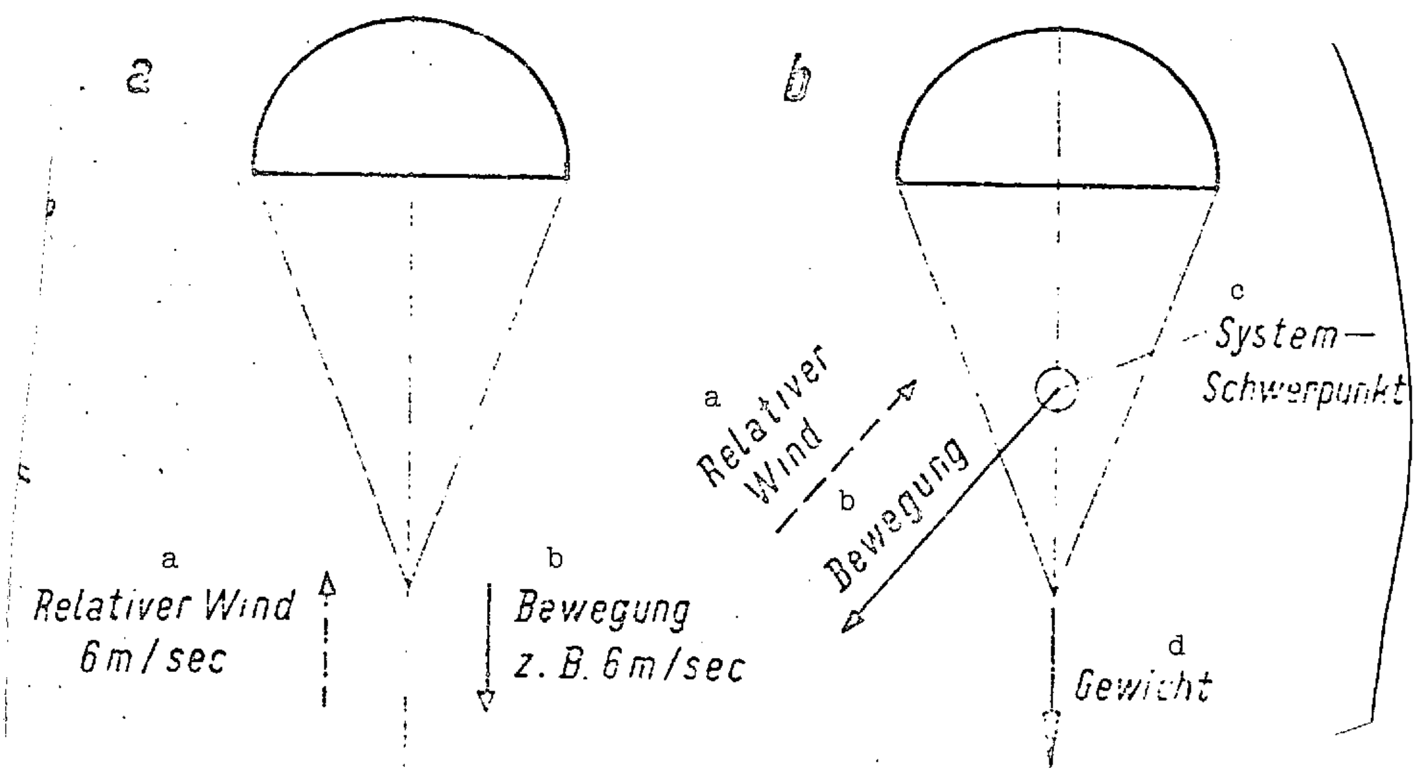


Fig. 4. Parachute motion. a) $\alpha_{stable} = 0°$; b) $\alpha_{stable} \approx 20°$.

Key: a. Relative air motion
b. Movement (z.b. = e.g.)
c. Center of gravity of system
d. Weight

Blenk: A clear distinction should be drawn between the question of stability and the question of damping. That which is called stabilization in this report I would call damping. Stability is determined by the sign of the differential quotient $dc_M/d\alpha$. However, whether the parachute swings and how vigorously it swings depends on the damping of the oscillation. The criterion here is the slope of the moment curve, i.e. the magnitude of the derivative $dc_M/d\alpha$. If the curve is very steep at the point of the stable attitude, the parachute will not swing very much; on the other hand, if it is flat, the parachute will swing quite a bit.

Thomanek: Does a parachute always swing in a single plane, or can it swing with a circular motion?

Heinrich: Both cases are possible. Moreover, a sliding process can be superimposed on the swing.

Blenk: Circular swings will always arise when there are any asymmetries, and the latter can occur very easily in a parachute. However, my guess is that a clean chute will swing in virtually a single plane.

Heinrich: This assumes that the parachute is large enough and is strongly damped.

Thomanek: With a given [illegible], how small can a parachute be made which will still stabilize and will suppress any swinging of the bomb suspended from it greater than ±2°, simultaneously causing the minimum possible drag?

Heinrich: For the 1000-kg bomb 62 cm in diameter, the best solution known to me was an 80-cm chute at a distance of 3.5-4 bomb diameters from the rear of the bomb.

Thomanek: Have there never been any attempts to use parachutes with diameters smaller than that of the load?

Heinrich: That didn't work, since the swinging was too violent.

In bomb stabilization, the cable arrangement plays a role. In this case, the so-called geodetic cabling (Fig. 5) is employed. It was developed in Stuttgart [next five lines illegible]. The angle between the ends of a cord, projected on the tail, is 90°. In this way, a system is obtained which will draw together in the case of a twist. This keeps the tail surface of the bomb parallel at all times to the entrance plane of the parachute.

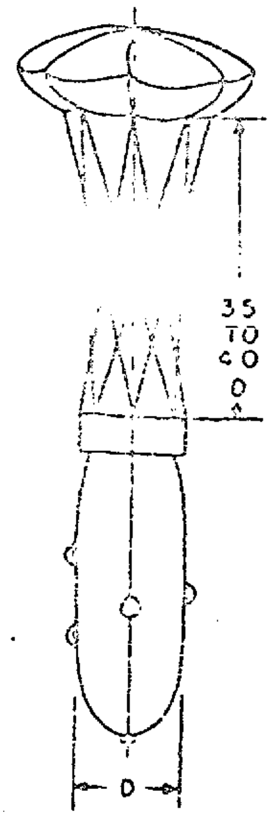


Fig. 5.
[illegible]

Thomanek: Was the final velocity of 180 m/sec for the 1000-kg bomb an objective? /39

Heinrich: No, it was a result, which was obtained.

Thomanek: Suppose that a higher velocity could not be obtained by changing the parachute diameter, because the stability would no longer be adequate. In that case, would it be possible to change the air permeability of the parachute, in order to obtain a higher velocity?

Heinrich: No, because the given conditions would be obtained with a stabilizing chute which was already pushed to the limit. If it were made any more permeable, it would no longer open. At its edge, the stabilizing parachute has the form of a cone, and the porosity must not be too great if the cone is to remain inflated.

Because of this cone, the stabilizing chute has the property that it always migrates into the dead water behind the bomb and remains roughly in its center. On the other hand, a ribbon parachute basically tries to get out of the dead water.

U. Schmidt: However, the ribbon chute only migrates out of the dead water when it is a planar ribbon chute. If the edge of the ribbon parachute is drawn in so that the resulting shape is similar to that of the stabilizing parachute, the ribbon chute also migrates into the dead water.

Heinrich: If a bomb is to be stabilized even at higher speeds, it can be given a small tail, which would take up very little room; by itself, it would not stabilize the bomb. Then, a smaller chute can be employed, so that the bomb would fall at a higher velocity.

STEERABLE PARACHUTES (G. Bünger) /40

Summary:

The possibility of obtaining better angles of descent for steerable parachutes by suitable shaping has been investigated. The idea was that the induced drag can be reduced by a higher aspect ratio even for spatially curved profiles, so that a higher lift-to-drag ratio can be achieved. Measurements on rigid ellipsoid half shells have been taken and analyzed to check out this idea.

1. Introduction /41

The field of problems covered by recovery technology has become much wider and more complex in recent decades. The requirements on the recovery systems can be divided into three large categories:

a) reliability,
b) simplicity of use,
c) steerability.

The systems designed to meet these requirements range from autorotation through folding wings to the parachute, which because of its structure, will at least satisfy the first two requirements best, and therefore plays a predominant role in recovery techniques. The parachute types which have been developed so far, such as the ring sail, the glide sail, and the parasail, do provide good steerability as far as the lateral direction is concerned, but there is not much chance of influencing the angle of descent. Known solutions regarding the lift-to-drag ratio and control of the angle of descent are still unsatisfactory.

2. Symbols

A [kg]	Lift
c_A [1]	Lift coefficient
c'_A [1]	Rise in lift for an airfoil with finite span (= $dc_A/d\alpha_g$)
$c'_{A\infty}$ [1]	Rise in lift for an airfoil with infinite span [= $(dc_A/d\alpha_g)_\infty$]
c_{MB} [1]	Moment coefficient, relative to top
c_N [1]	Normal-force coefficient
c_T [1]	Tangential-force coefficient

c_W [1]	Drag coefficient, relative to projected area of canopy
c_{WD} [1]	Coefficient of pressure drag
c_{Wi} [1]	Coefficient of induced drag
c_{WR} [1]	Coefficient of friction drag /42
f [%]	Curvature, relative to semiminor axis of the ellipsoid
I [kg sec]	Momentum
q [mm H_2O]	Stagnation pressure
R [kg]	Force resultant from lift and drag
U_∞ [m/sec]	Freestream velocity
W_i [m/sec]	Induced downwash
W_i [kg]	Induced drag
α [°]	Angle of attack, measured from line of symmetry of parachute model
α_e [°]	Effective angle of attack
α_g [°]	Total angle of attack (= 90 - α)
α_i [°]	Induced angle of attack
Λ [1]	Aspect ratio

3. Aerodynamic Possibilities for Obtaining a Given Angle of Descent

The methods used so far for obtaining forward thrust, and thus a better angle of descent, has been to put slits in the back of the parachute, so that air can flow out of the canopy, the flow being variable in magnitude and direction. Momentum conservation pushes the parachute and its load forward (Fig. 1). One consequence is that the flow does not separate as soon as it approaches the edge, instead remaining against the chute for considerably longer, thus generating an additional lift for forward thrust.

Another possibility for improving the angle of descent consists in reducing the drag. The drag coefficient is made up of the following terms:

$$c_W = c_{WD} + c_{WR} = c_{Wi}$$

The pressure and friction components cannot be influenced very /43
much; on the other hand it ought to be possible to diminish the induced drag by increasing the aspect ratio.

The relationships between lift, induced drag, and aspect ratio can be determined as follows. The angle of attack relative to a profile section consists of an effective term and an induced term (Fig. 2).

$$\alpha_g = \alpha_e + \alpha_i.$$

In order to show that for an object with a large dead water, the induced drag could be decreased by reducing α_i, measurements were taken on rigid elliptical half shells with an aspect ratio from 1:1 through 1:3. The results of these measurements demonstrate that the induced drag is a function of the lift coefficient c_A and the aspect ratio Λ similar to the corresponding function for an airfoil. The equations for the two-dimensional wing cannot be used here, since, with a skeleton profile involving curvature along two axes, as in the case of the parachute canopy, the flow cannot be considered two-dimensional, and also because the angle of attack α_g is generally large.

A comparison with theory for an airfoil of finite span shows a similar tendency for the lift increase $dc_A/d\alpha_g$ (Fig. 5).

4. Experiments

4.1. Apparatus

The models were suspended from clamps at the top of the canopy and at the intersection of the cords (Fig. 3). The fixed points were fastened with a bracing assembly to a turntable, with which the angle of attack could be varied from 0° to 90° in intervals of 5°. The four measuring points of the two strain gauge balances were hooked up through an amplifier to the Honeywell 1508 Visicorder and the PI tape recorder. A program control marked off every 5 sec of measuring time on the two devices. The stagnation pressure was recorded directly on tape.

The tape recorder recorded on seven tracks the four force values, the stagnation pressure, the time record, and the statement of the experiment number. In order to keep the tape speed as uniform as possible, a stabilizer was used for the program control and the tape recorder. /44

The Visicorder made it possible to monitor the recording of the measurements visually. It was not actuated by the program control, but by hand.

4.2. Procedure

The experiments were carried out with stagnation pressures of 70 and 100 mm H_2O. The angle of attack was varied from 0° to 90°

in intervals of 5°. Stagnation pressures lower than 70 mm H_2O were not possible, since there were strong oscillations in the wind tunnel despite the installation of additional screens. After each pass, the strain gauge balances were checked, and if necessary, realigned. The zero points remained relatively stationary.

4.3. Results of the Measurements

Analysis of the measurements yielded properties for the aerodynamic coefficients similar to those for a normal profile (Fig. 4). The values of c_A and c_W exhibited a roughly linear rise for small angles of attack α_g or large angles α. The maximum of c_A occurred between 50° and 70°, while c_A/c_W had the best values in the range 60-75°. The moment changed little as a function of α, so that this parachute shape is not very stable. The polar curve c_A vs. c_W was plotted for the entire measuring range.

As a comparison, the theoretical lift increase $dc_A/d\alpha_g$ of a two-dimensional finite airfoil as a function of Λ is also included in Figs. 5 and 6. With a larger aspect ratio, the measurements approach the theoretical curve, since the shape of the model approximates a two-dimensional profile.

5. Practical Experience /45

So far, a prototype with a maximum diameter of 3 m has been assembled and tried out in a few drops. Gliding ratios of about 1:1.5 were obtained. The model had an axis ratio of 1:3, and the curvature was 100%. Control was attained via two vents at the rear of the canopy.

The main problem was keeping the front edge stable. In opening, the parachute is very reliable. Gusts can very easily cause pitching oscillations.

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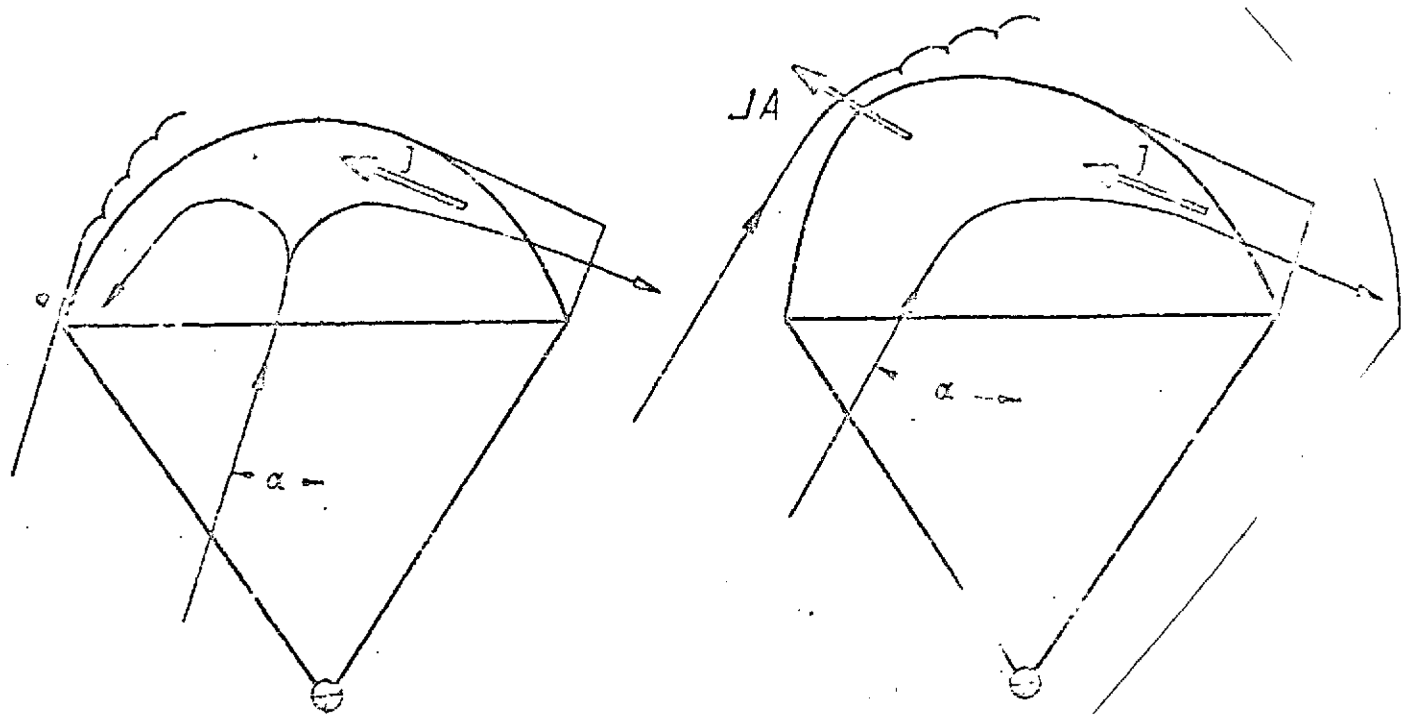


Fig. 1. Two examples of ways to improve forward thrust and lift in a parachute.

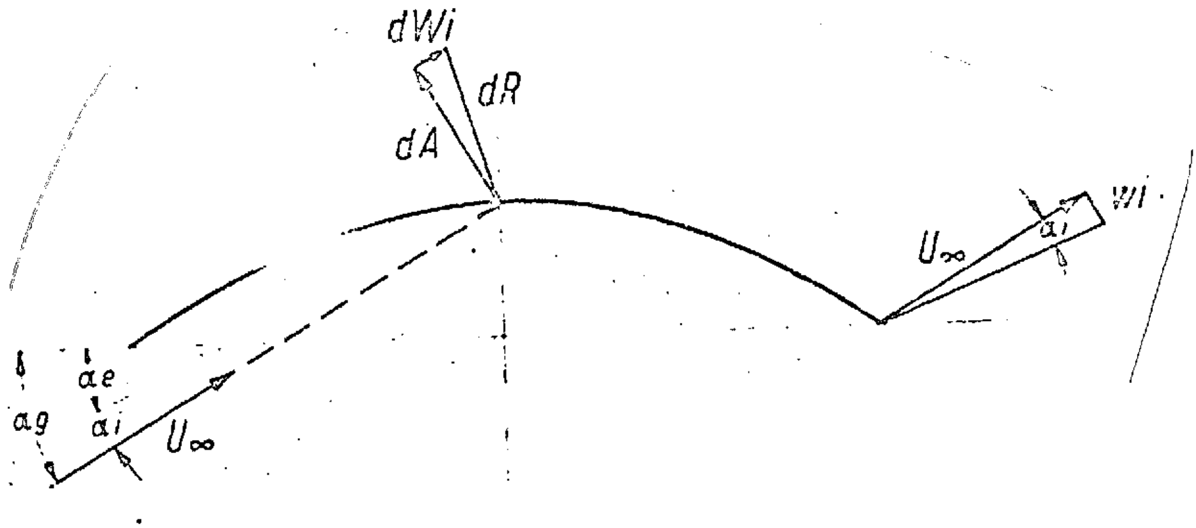


Fig. 2. Schematic of aerodynamic parameters along a profile section.

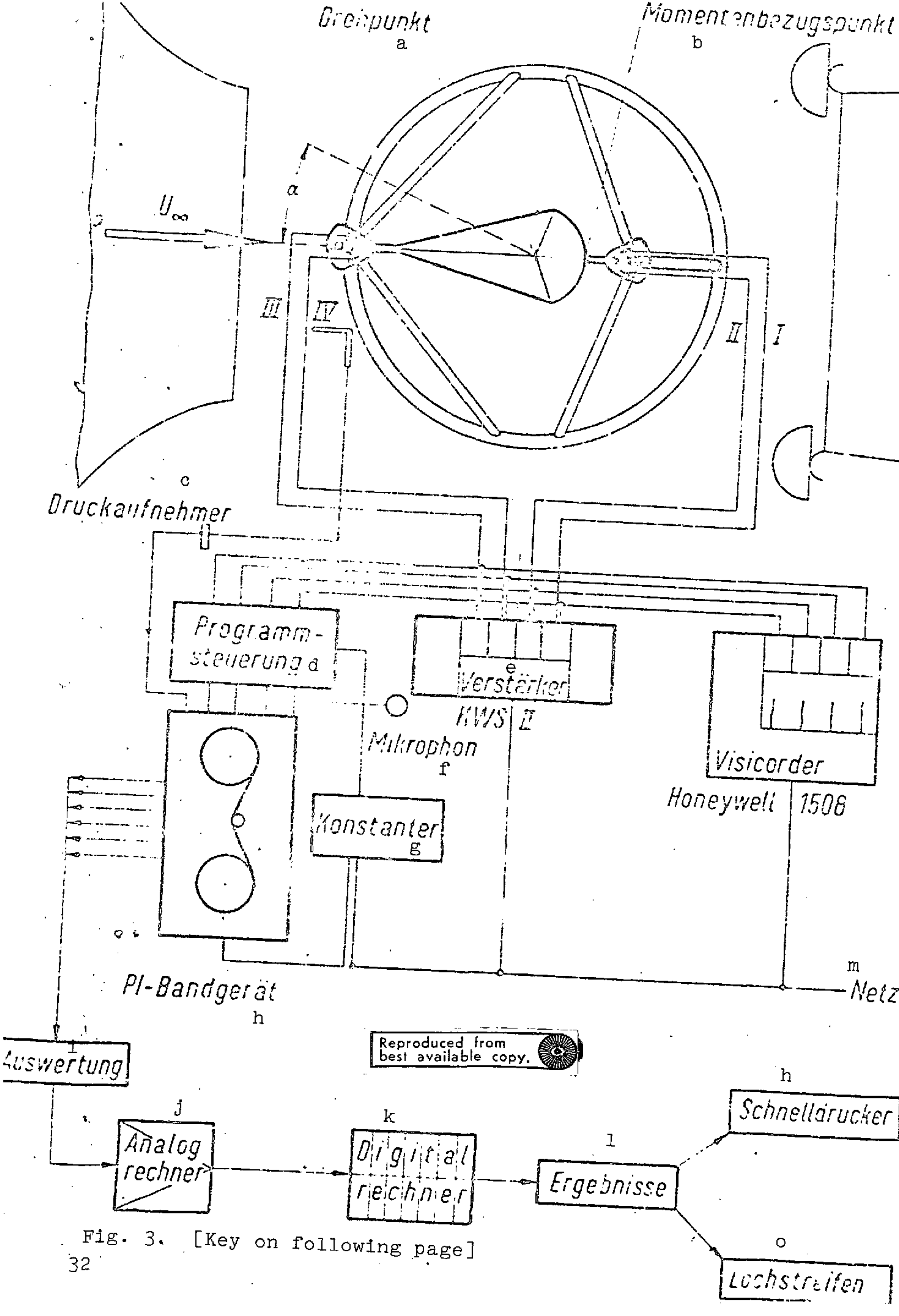
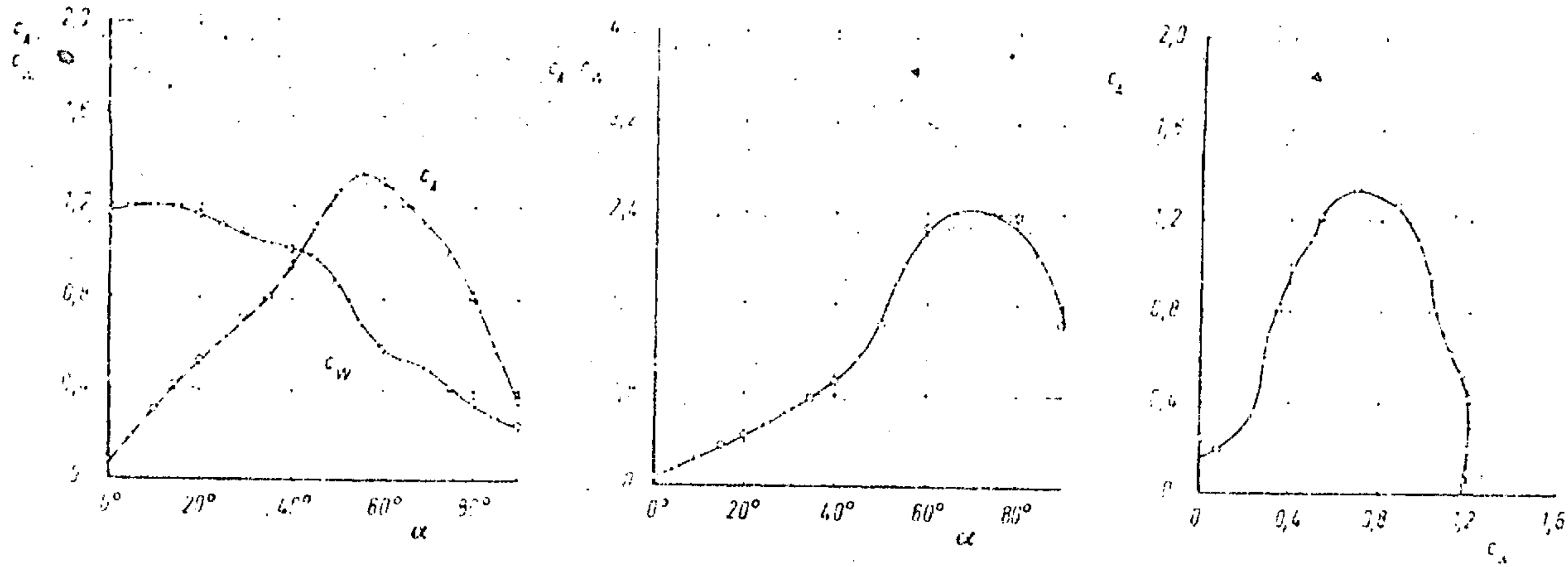


Fig. 3. [Key on following page]

Key to Fig. 3

a. Pivot
b. Reference point for moment
c. Pressure sensor
d. Program control
e. Amplifier
f. Microphone
g. Stabilizer
h. Tape recorder
i. Analysis
j. Analog computer
k. Digital computer
l. Results
m. Power source
n. High-speed printer
o. Punched tape



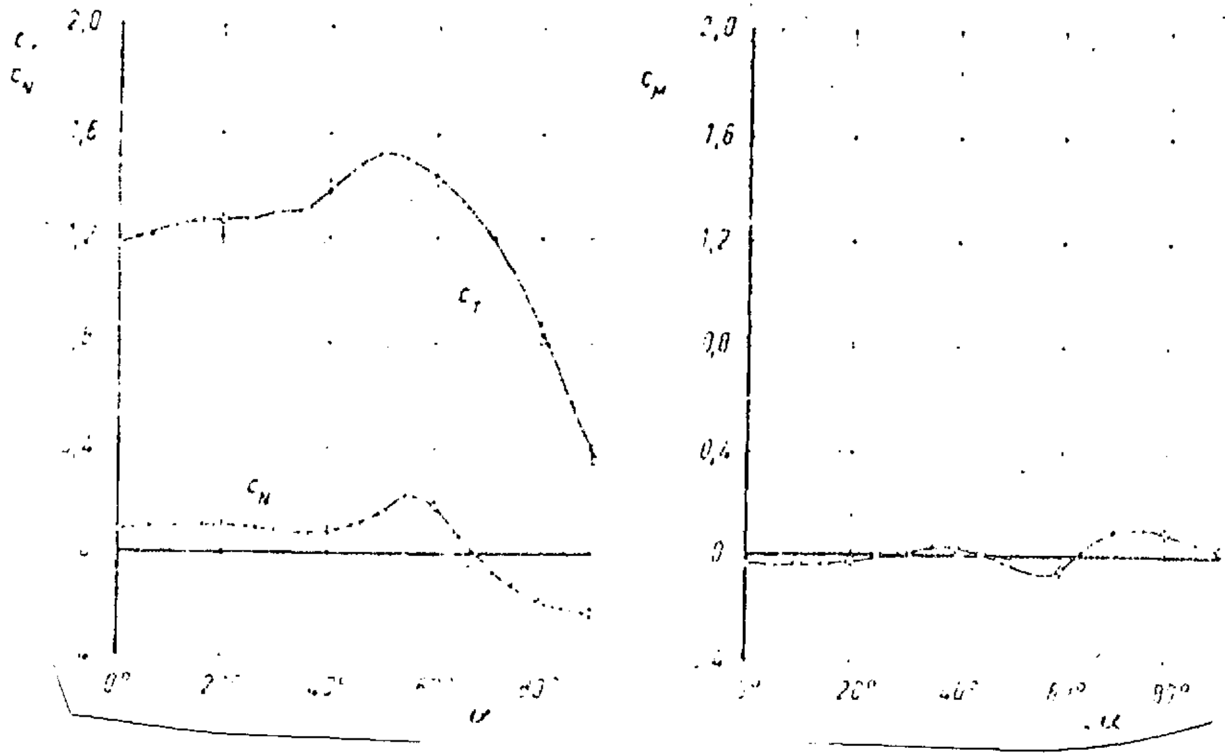


Fig. 4. Aerodynamic coefficients and polar curves of an elliptical gliding chute.

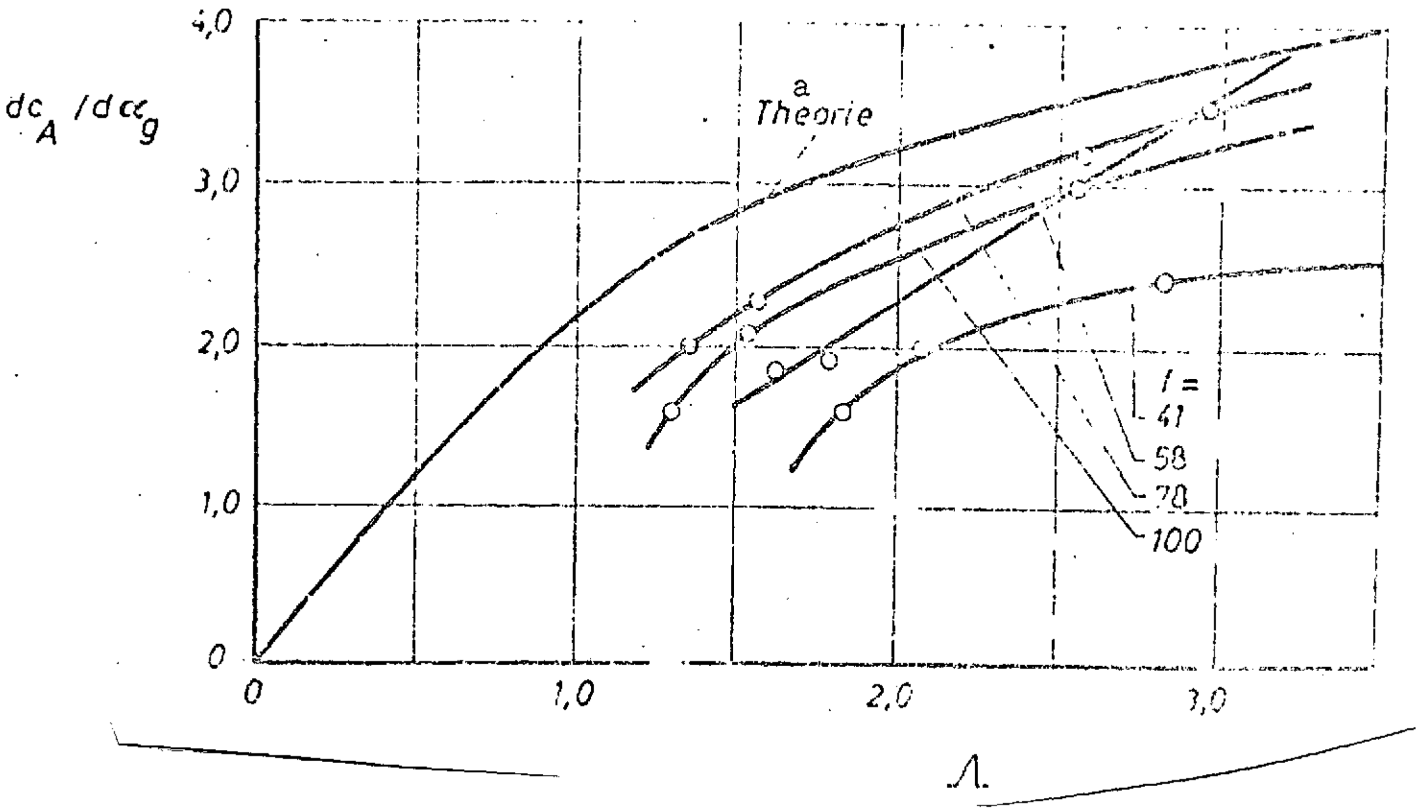


Fig. 5. Increase in lift as a function of aspect ratio with curvature as a parameter. Comparison of measurements with values given by two-dimensional airfoil theory.

Key: a. Theory

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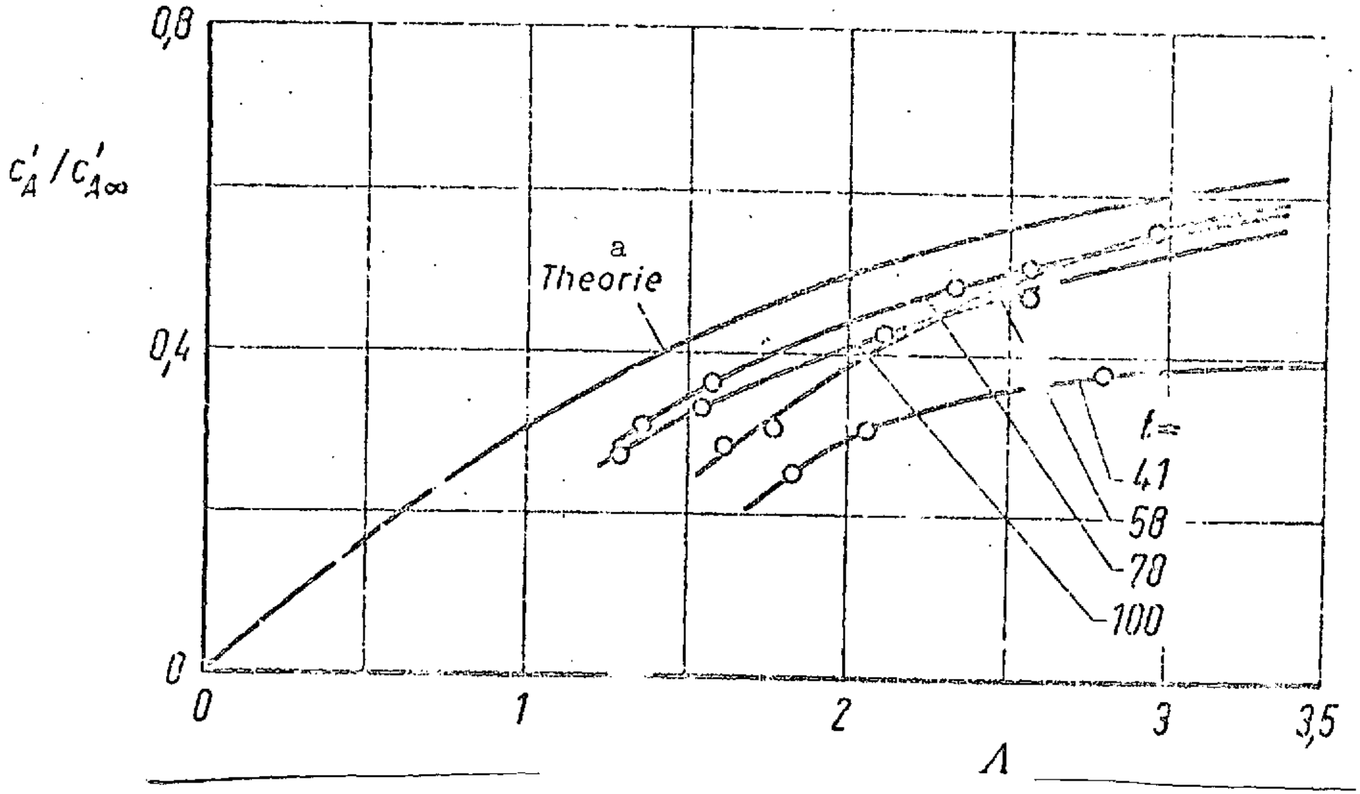

Fig. 6. Ratio of lift increase for finite/infinitely long airfoil vs. aspect ratio with curvature as parameter.

Key: a. Theory

Heinrich: In the U.S., there are quite a few really functional systems descended from the parachute family, but which no longer resemble the conventional parachute very much. One of the first successful gliding parachutes was the so-called Parasail (Fig. 7). This parachute is asymmetric, and has an intact canopy on the leading edge. The trailing edge looks something like a ring slot parachute. This is the effect which Bünger explained, with the outflow toward the rear and the attached flow forward, producing a glide. In a full-scale test (up to 80 ft diameter), this parachute had a lift-to-drag ratio of about 1.3.

Fig. 8 shows the cloverleaf. It consists of three separate canopies, sewn together so that a desired aspect ratio is obtained. Moreover, since there are three individual canopies, the indentation of the leading edge does not have such a disturbing effect as with the parasail. Because of this indentation, the lift-to-drag ratio for the parasail was limited. The cloverleaf has a better aspect ratio and less indentation. In this case, a lift-to-drag ratio of about 1.7 has been achieved. The parasail and the cloverleaf are still genuine parachutes.

Since then, further items have been developed. One is a type of elliptical chute designed by David Barrisch called the sailwing (Fig. 9). In essence, it consists of a surface, curved no more than slightly, the shape of which is preserved by a /52
particular kind of frame. According to reliable figures, lift-to-drag ratios on the order of 3 have been obtained. Jumps have also been made with the parachute.

Another construction with a great similarity of profile is the so-called parafoil (Fig. 10), consisting in essence of a structure, of a type of sack, which has a wing extension and which is curved at the top and bottom. The leading edge of the wing is open, so that the stagnation pressure pushes inward, inflating the structure, keeping it rigid, and thus providing a genuine wing profile. People have already made jumps with this one as well. Again, they have obtained lift/drag ratios on the order of 3. This then is a really flat glide. The porosity of the fabric of this parachute is astonishingly low; the low permeability to air is obtained by pressing the fabric very hard. I was told that the permeability to air was essentially zero, even without a plastic coating. This construction has also been used as a kite, in order to lift antennas into the air. People have been experimenting with it for several years, but the first jump tests have just been made.

Bünger: Could you say something about the reliability of opening?

Heinrich: I believe it is still too early to say. In any case, people have jumped with it out of private planes. One can recognize the efforts to generate these aerodynamic forms by construction with the aid of flexible frames. You can see the slight curvature, required for static reasons, since the cords will always have a lateral-force components. The surfaces can be /53 brought to positive and negative angles of attack, so that the glide angle can be regulated as well. According to jumpers' reports, one can actually flatten out quite well in landing, by floating in at a steep angle and drawing up the nose at the last moment before the landing, producing a large positive angle of attack.

Fig. 11 shows a parawing, the development of Mr. Regallo. This is a single-cloth structure, with which lift/drag ratios of 3 have been obtained. It is perhaps lighter and less bulky than the airfoil structure. So far, it has not been determined which of the two designs produces a larger lift/drag ratio. In terms of a given weight and given volume when packed, the parawing may be preferable. It is probably not as sensitive with respect to permeability. Of course, it will still be some years before such parachutes can be made larger. So far, they have only been produced in jumper sizes.

The picture shows an interesting aerodynamic feature: the "domed" leading edge. Hence, it is cut so that the leading edge bulges out, preventing indentation. In my view, this rounded leading edge is a very clever construction.

The same construction has been built by Irvin, under the name Manta Ray. Figs. 12 and 13 show the Hawk and Eagle models. The cut is the important thing, the truncated tip.

U. Schmidt: Are the porosities of these two types different? /54

Karck: There are two systems, one with a continuous canopy with no opening, and the other with a canopy with appropriate openings. The parachute used recently in jumps has essentially the closed canopy which is completely impermeable to air. It is made of a special fabric.

Hoenen: As a parachute jumper, perhaps I can add something. The safety of these types of parachutes is not particularly high. Even a so-called Paracommander (Fig. 14) is not as safe as an ordinary jump chute, since there is the danger that the parachute will collapse from the front, producing a so-called malfunction, a faulty opening. As a result, the jumper must discard the parachute and make an emergency landing with the reserve parachute.

Brüggemann: Test jumpers of Pioneer bring about this effect of frontal collapse three or four times during a drop. By pulling both cords, the situation can be corrected. New operating instructions are soon to be issued for the Paracommander, describing this parachute behavior, which is important for jumpers.

Hoenen: It is true that a mild malfunction can be corrected by pulling both control cords. However, in the "flash" figure, for example, in which a jumper no longer falls vertically, but with a forward component, the malfunction can be so great that the parachute gets all tangled up and it can no longer be controlled by pulling the cords. During the malfunction, the chute /55 bulges inward from the front, the side slits press the lateral parts of the canopy forward, and the entire system begins to rotate. The parachute then gets tangled up.

Schulz: Are all these parachutes packed in the normal manner, or are special measures taken?

Hoenen: These parachutes are placed in a packing tube which is drawn out by the auxiliary parachute. We have tried out some other packing methods, but no better one has been found.

Ahlborn: With the wing configurations, which still have a relatively impermeable fabric, is the opening shock greater than that of normal parachutes?

Hoenen: I can only say that the Paracommander gives a somewhat greater opening shock than ordinary parachutes do.

Karck: With the parawing, the problem of the opening shock is rather critical, and a large number of experiments have been conducted with the objective of reducing it. Irvin Paraspace in the U.S. has now managed to reduced the opening shock to about the same level as that produced by a normal jump parachute.

Hoenen: The opening shock can be reduced somewhat by using a small auxiliary chute and prolonging the opening somewhat. This has sometimes been done in America as well.

Heinrich: However, this impairs safety.

Bünger: Is it possible to have the inflation process take /56 place slowly in the reefed state, and then release the parachute gradually, and not suddenly?

Heinrich: In general, reef cords and tied-off cords are not recommended for parachute jumpers. I don't really believe that sport jumpers suffer very much from the opening jolt. After all, the jumps are usually made at low velocities.

Hoenen: Normally, jumpers do not suffer from the opening jolt. That is no problem either. The problem with the Parac

Paracommander is only that it has opening difficulties. Perhaps I should mention the Olympic parachute, a side development of the EFA. The parachute has roughly the same construction, except for the fact that there are air inlet slits at the front edge, thus stabilizing the edge somewhat. However, not enough experience is available yet, so that it is impossible to say whether this will eliminate the opening difficulties.

Heinrich: The slits in the front side cause a loss in lift. Moreover, these parachutes bulge inward more easily when there are slits in the front. A lot of lift is lost.

Brüggemann: Hasn't Pioneer abandoned the slits for that reason? They first had slits in the front, and then eliminated them, unlike Lemoinge.

Heinrich: NASA also did away with the front slits, because of the loss in lift, because the front indents, and because the parachutes have too high a porosity anyway. If the porosity can be reduced by 5%, the safety can be increased by the same amount.

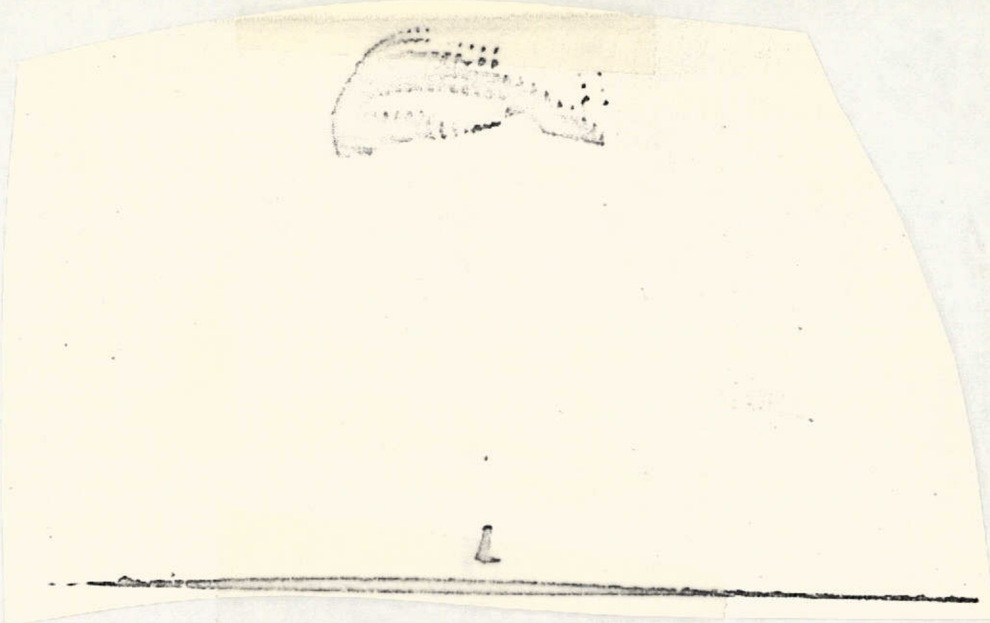

Fig. 7. Parasail (D_o = 80 ft)

Fig. 8. Cloverleaf (back side).

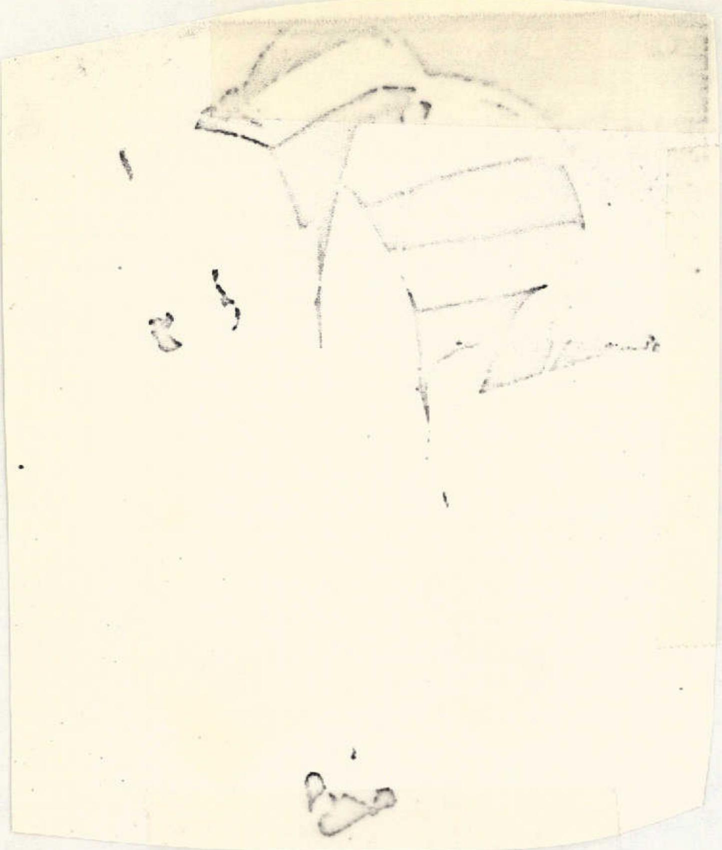

Fig. 9. Sailwing
(leading edge right)

Fig. 10. Parafoil

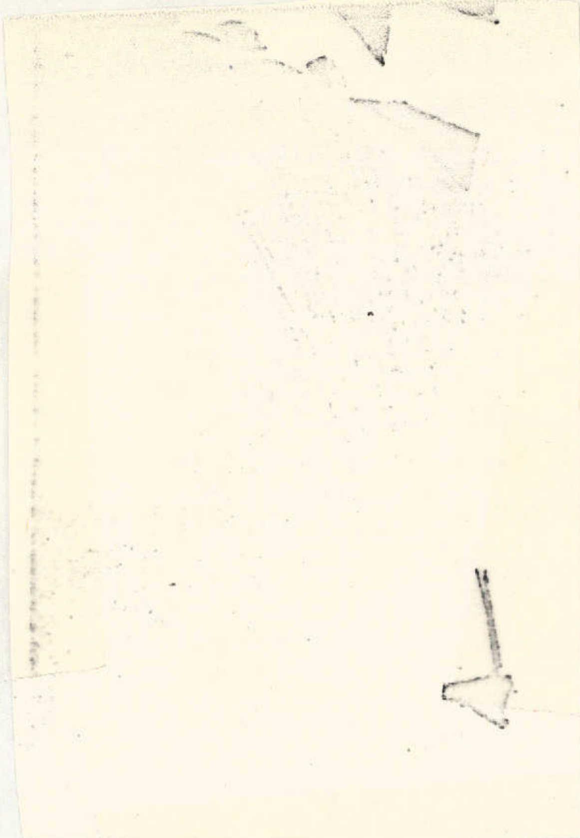

Fig. 11. Parawing
(Rogallo)

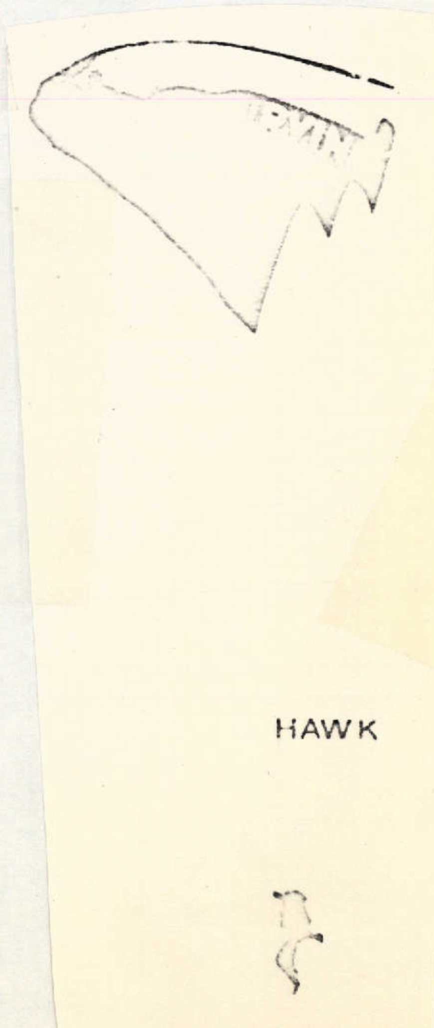

Fig. 12. Manta Ray, Type H
Hawk.

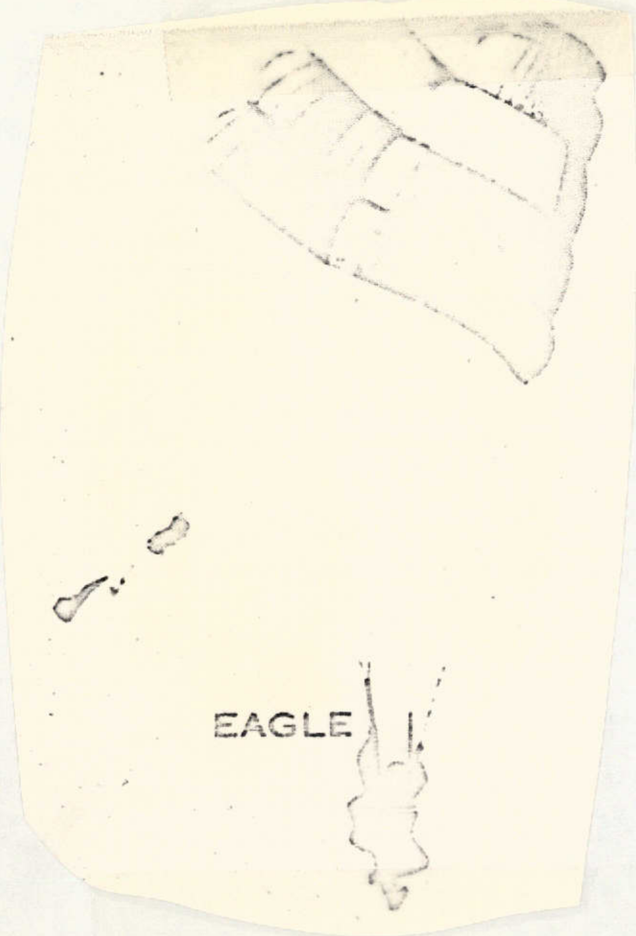

Fig. 13. Manta Ray,
Type Eagle

Fig. 14. Paracommander

CLOTHS, RIBBONS, AND CORDS FOR PARACHUTES (K. Lorke) /61

Parachute textiles are the weight-bearing components of parachutes. They should therefore be subject to careful selection and testing as well as constant supervision with respect to the special requirements arising from their use in parachutes.

It is true that there are a number of excellent textile research institutions in West Germany, but their main effort is centered on the demands of the "civil sector," i.e. for clothing and textiles in the home, which are afterall consumed in the largest quantities. The "technical sector" is interested mainly in filter cloths and textile linings for automobile tires, etc. Trailing at a great distance we find parachute textiles, which consume an extremely modest proportion of the raw materials. It is therefore understandable that no special allowance has been made for the particular needs of parachute construction in general textile research and development.

This is the point at which the activity of the textile experts of the DVL (with their own textile laboratory adapted to the needs of aeronautics) begins. However, their work is readily assisted and supported by prominent specialists in the chemical fiber industry and from research institutes. Of the latter, particular mention should be given to

Prof. Dr. Paul-August Koch (fiber technologist, director of the State Textile Engineer School in Krefeld),

Prof. Dr. Helmut Köb (Farbwerke Hoechst AG, Bobingen factory and Munich Technical University),

Prof. Dr. H. Müller (Stuttgart Technical University, Institute for Mechanical Conveying),

Prof. Dr. Walter Wegener (Aachen Technical University, Textile Institute).

The DFL works on textiles not only for parachutes but also for airborne equipment, recovery equipment, pneumatic life rafts, lifejackets, and aircraft fabrics. Textile problems are subjected to the following two-pronged attack: /62

The textile laboratory carries out the mechanical-technological and physical investigations, works up studies, and deals with practical research.

The textile department of the testing division evaluates these researches using the criteria of maximum safety and the requirements of parachute manufacturers or the special offices of the

Federal Defense Forces. It draws up specifications, divided into test values and production directions, for detailed inspections and current production. The determination of actual functional values is a particular objective. Here too, the special testing directions for aerodynamic textiles are worked out.

Among all the possible topics, we will now select several of the greatest interest:

Textile Raw Materials Used in Parachute Construction

Because of the continuing progress in the development of synthetic fibers, the latter have virtually completely replaced natural fibers in recent years in parachute construction, since the quality of natural fibers is largely a function of the crop. In selecting synthetic fibers from the wide assortment available, not only the basic requirements (strength, elongation, melting point, weight, etc.) but also the assurance of a uniform product quality must be taken into account.

In the 50's, the decision fell on the German polyamide brand "Perlon," in which large fluctuations in the technological values were not anticipated. In the meantime, however, the polyamide "Nylon 66" has been further developed, and many German manufacturers guarantee adherence to standards for this product which are within the requirements for aerodynamic textiles. Another ad- /63
vantage of "Nylon 66" is that the melting point is about 30°C higher.

Elastic Cloth

The textured yarns (termed "Helanca" in ordinary speech) used for some years for hose, foundation garments, ski pants, etc. led to the development of elastic cloth for parachute canopies.

In a concluding "Report on studies on synthetic textiles from textured yarns for high-performance parachutes" of the DFL of February 1966, the successful results are presented in detail [1]. They are based on the fact that, because of the elasticity of the cloth, the permeability to air rises almost tenfold in the presently measurable range from 16 to 350 mm H_2O. Practical tests found that the opening shock was considerably reduced, but the high-performance limits of parachutes made of elastic fabrics could not be determined because of insufficiently fast test stands.

Nonwoven Flat Textiles

Samples of the fiber-reinforced nonwoven fabrics which have attracted attention in the last 2 years and which are produced by various processes have already been given to the DFL so that the latter can assess the chances for using them in parachute construction. The studies on these materials have not yet been concluded, but suggest some positive surprises.

Loading Belts for Heavy Loads in Air Transport

With these belts, the dimensions of which must be adapted to the devices on which they are to be used, the problems of flexibility, loop sewing, and dynamic load capacity are of primary interest.

In order to approach the optimum with the practical values, systematic seam studies and dynamic tensile tests were carried out, which will be reported at the proper time.

Fireproof or Fire-Resistant Parachute Textiles /64

Since the effects of fireproofing materials are generally related to the thickness of the layer of the substance on the textile product, no usable and sufficiently inexpensive compound has been found for parachute textiles, although complex experiments have been going on for years.

REFERENCES

1. Lorke, K. and Seifert, K.-J., "Report on investigations of synthetic textiles of textured yarn for high-performance parachutes," unpublished in-house report of the DFL, Braunschweig, 1966.

PROBLEMS OF MEASURING TECHNOLOGY (H.-J. Klewe) /65

Summary:

The following short report deals with problems in measuring technology involved with the study of parachutes. Among the topics to be discussed are sensors, measuring and recording techniques, models, and telemetry and control units. The special problems which arise and possible solutions are outlined.

Introduction /66

As part of this symposium, we will now discuss problems in measuring technology as they affect the study of parachutes. Since we cannot give an exhaustive presentation of all the problems at this time, we will single out a few details and first say something about the sensors used for measuring the various quantities. We will then give a brief outline of our transmission system. In general, in the study of parachutes, the quantities which are measured are the forces in the cords or in the belts to which the cords are attached, and the pressure distribution in the parachute during inflation or in the steady state after inflation. Also of interest is the change in diameter of the parachute during deployment. In order to be able to determine the latter quantities, and thus the area of the parachute during the various phases of inflation, the process is filmed with a high-speed camera.

Pressure Sensors

Pressure sensors were initially not available for measuring the pressure distribution on the parachute. Commercial pressure sensors were generally too large or too heavy, so that they could not be attached to the parachute -- the sensor itself would have falsified the result of the measurement. Therefore, the first task was to create a pressure sensor for this purpose, one which would have a small mass, in order not to falsify the measurement, and one which would also be very sensitive, since the pressure differences to be measured, particularly in the steady state after inflation, are very small. Furthermore, the sensor must be acceleration-compensated, since there are appreciable vibratory accelerations during the deployment of the parachute, and these will act on the sensor and may result in completely incorrect measurements in noncompensated sensors. Such a sensor was developed at the Institute for Flight Mechanics. Following various considerations regarding the measuring principle, this sensor was designed with strain gauges. Fig. 1 shows a section of the sensor, which is situated in the housing 1-3. The diaphragm, made /67
of a [illegible] foil 4 and the aluminum parts 5, 6, and 7, picks up the pressure to be measured, and transmits the force exerted by

it through a connecting wire 13 to a bending element 10, to which two strain gauges are glued on each side. These strain gauges are wired together in a Wheatstone bridge circuit, which delivers an appropriate electrical output signal when pressure is applied to the diaphragm. At the ends of the bending element 10, there are weights 12, which, when the system is accelerated, cause the bending element 10 to bend, a motion which is opposed by the force induced by the mass of the diaphragm and the bending element itself, so that the acceleration is compensated. Further details will be provided in connection with Fig. 3.

The pressure sensors have a measuring range of ±200 mm H_2O, i.e. it is essentially linear in this range. Its weight is 9 g, its diameter 30 mm, its height 8 mm, and the maximum length about 40 mm. The strain gauge bridge circuit has a bridge resistance of 120 Ohm. The output voltage delivered by the pressure sensor can be seen in Fig. 2. The output voltage is plotted in mV/V bridge input voltage against the pressure difference. The bridge input voltage is generally 6 V in the circuits we have been using. The characteristic is essentially linear in the range of ±200 mm H_2O. An overload up to about 350 mm H_2O is permissible, i.e. after such an overload, the characteristic remains essentially linear.

Fig. 3 shows error curves giving the error of measurement in relation to the acceleration or the frequency of the vibrational acceleration. At the top, the error of the output signal in percent is plotted against acceleration, up to about 220 g, for a load of 200 mm H_2O. The acceleration was generated in the laboratory with a centrifuge. Accelerations up to about 200 g on the parachute cloth must be anticipated when the parachute is /68 inflating. In that case, however, the accelerations involved are vibrational, i.e. the entire sensor system is exposed to such a vibrational acceleration. [Illegible] ... this load was simulated in the laboratory on a vibrating table and the measurement error in percent was plotted against the frequency at constant acceleration. [Next sentence illegible] In this case, this occurs at a frequency of about 235 Hz. Inferences could also be drawn about the natural frequency of the sensor, since experience has shown that the natural frequency is close to the frequency at which the system vibrates most strongly in response to external excitation. In fact, when alternating pressures are applied to the sensor, a somewhat different natural frequency will be observed, since it is only the actual measuring system of the sensor which responds. However, this is very difficult to approach experimentally, since it is by no means easy to create a device which will generate such alternating pressures up to a very high frequency, and will maintain a constant amplitude with increasing frequency.

The pressure sensors required by the Parachute Engineering Division of the Institute for Flight Mechanics for their measurements were put together by this division itself. Naturally, there were engineering problems involved with this production. It is relatively difficult to manufacture such sensors reproducibly, in order to obtain the same characteristic parameters and the same quality in a series of sensors. Quite apart from the facts that extreme precision is required in the mechanical production of the various components -- assembly is carried out with the aid of a microscope -- and that the specifications of the materials employed must be met very exactly, particular difficulties arise in gluing the strain gauges to the bending element. For one thing, the quality of the glue differed from one shipment to the next, so that the resulting hardness was not always the same. For another thing, because of the heat load on the strain gauges, through which a current of about 50 mA flows in our circut, and because of the fact that the bending element cannot carry off much heat, the strain gauges, and thus the glued connections, heat up, so that if the proper conditions are not adhered to during gluing, or if later the bridge input voltage is allowed to exceed the permissible limit, the glue -- single-component glues were usually employed, and the glue was applied cold -- hardens further by an undefined amount and stiffens the bending element to such an extent that there will be a loss in sensitivity later. Thus, both during production and during measurement, one must proceed very carefully. /69

Force Pickups

The forces in the cords were measured with force pickups likewise made in the Parachute Division of the Institute for Flight Mechanics. These pickups also operate on the strain gauge principle and convert the strains on a ring, to which the strain gauges are glued, caused by the tensile forces into an electrical output signal. The force pickups were inserted directly into the belts between the load and the cords of the parachute.

Measuring and Recording Techniques

Measurements on parachutes were carried out by the Parachute Division of the Institute for Flight Mechanics both in the wind tunnel and in the free atmosphere. When measuring in the wind tunnel, the parachute was fastened at the junction of the cords, and released once the wind tunnel had been run up to the desired speed. The output signals delivered by the pressure and force pickups were then fed to a carrier-frequency measuring bridge, and the output signal of the latter was fed to a recording device. Instead of discussing this well-known technology, we will make some remarks on the measurements taken in the free air. Pressures and forces were again measured, the appropriate pickups being arranged on the parachute in the same way as in the wind tunnel experiments. Other values such as stagnation pressure and total pressure are also involved. The problem of greatest interest is how the parachute measurements are to be subjected to further analysis. A procedure which has been and continues to be used in /70 the Parachute Division involves recording the data with a device, writing on photosensitive paper, in a measuring doll, representing the load carried by the parachute. The signals can be simultaneously recorded with this recorder. This procedure, although it has worked well, has several drawbacks. For one thing, the photosensitive recording paper must be developed after the experiment. This takes time and precludes the possibility of seeing, immediately after the experiment, what the measurements have yielded and whether errors have occurred. Secondly, the measurements recorded on the paper are fixed in this form, and are no longer available in electrical form, so that the paper tape must necessarily be analyzed. It is true that at the Institute for Flight Mechanics, measurements recorded in such a form can be digitalized with a device present for this purpose and analyzed further later. However, it would be useful to receive the measurements on the ground in a form suitable both for an analog record, e.g. on photosensitive or UV-sensitive paper, and for direct input into the Institute's computers, which would also permit direct observation of the processes. One possible way of storing the signals in electrical form would be to install a tape recorder in the measuring doll or in a flight model representing the load on the parachute. Such a device must be [illegible], have sufficiently many signal recording channels, and be mechanically stable and shock-resistant, so that it will not be damaged e.g. in rather hard landings. Unfortunately, commercial devices of this type are relatively expensive and generally suitable only for signal input. Therefore, what is required is a device suitable for reproduction on the ground, to read out the stored data. Furthermore, when tape recorders are used, it is still impossible to observe whether or not the measurements have been successful. Hence, the best way seemed to be to provide telemetry equipment for transmitting the measurements. [Next sentence illegible]. Before describing the telemetry equipment used in the Parachute Division, we will give a brief description of the model likewise developed in the Parachute Division of the Institute for Flight Mechanics. /71

Model

The model depicted in Fig. 4 has an aerodynamically favorable shape, which is necessary to permit certain measurements, and offers sufficient room in its interior to accommodate the required apparatus and safety devices. It consists of three sections and a tip of damping material, in order to absorb the landing shock. At the very front of the model is attached a stagnation tube, in order to measure the speed of the model. The stagnation-tube support is simultaneously used as an antenna for the command receiver. In the tip mentioned above, there is a section housing the telemetry unit, a command receiver unit, a time switch, batteries as the system's power supply, and other circuit components. On the outside of this section are two diametrically opposed quarter-wave bars, which serve as the transmitting antennas for the telemetry unit. The next section contains a recovery system, i.e. a second parachute, which can be deployed at a command from the ground when the test parachute malfunctions so that the model is in danger of crashing. The tail section of the model contains the test parachute and a camera to film the inflation of the parachute. The release of the test parachute or, if necessary, the recovery system is accomplished by a pyrotechnic process, and is directed by the timing switch mentioned above or by the control unit. Once the measuring process has been completed, the stagnation tube with its support is detached pyrotechnically from the model, and carried to the ground by a special parachute. The control unit was a commercial remote-control radio unit operating in the 27 MHz range. Since there are many interferences in this frequency range due to radio telephone systems, diathermy machines, and the like, this remote control unit was adapted to the requirements. In particular, the signals were coded in the transmission channels, in order to rule out the possibility of spurious commands and thus faulty releases.

Telemetry Unit /72

The signal transmission method selected for the telemetry unit was the FM-FM method, since several signals must be transmitted simultaneously with relatively high signal frequencies (rise time 7 msec). These high signal frequencies occur both during force measurements and pressure measurements, the shortest signal rise times being anticipated for the pressure sensor at the edge of the parachute. Fig. 5 shows a block diagram of the FM-FM telemetry unit employed. FM-FM means that in this method, the signal undergoes frequency modulation twice. The left side of the block diagram shows the on-board unit. At the far left is the measuring equipment, i.e. the pressure and force pickups. The signals from these sensors are fed to so-called subcarrier oscillators. These are oscillators which vibrate at a specific frequency in the low-frequency range, and which change frequency in response to the direct-current signals supplied by the sensors, and are thus frequency-modulated. The output signals of the subcarrier oscillators are combined and fed to a mixing amplifier, which amplifies the mixed signal and feeds it to the transmitter as a modulating signal.

The transmitter likewise oscillates at a specific frequency. The Federal Post Office has assigned the frequency 232.5 MHz to the Institute for Flight Mechanics for this purpose. The frequency is modulated by the mixed or frequency multiplex signal delivered by the mixing amplifier, thus producing a second frequency modulation, and the modulated frequency is beamed out through the transmitting antenna.

The right side of the block diagram shows the receiving unit. This consists of a receiver, the subcarrier discriminators, appropriate amplifiers, and recording devices. The receiver, which is depicted in the rectangle enclosed in the dotted lines at the top left of the right-hand part of the picture, was constructed in the Parachute Division of the Institute for Flight Mechanics, and consists of a commercial TV VHF tuner with voltage-variable capacitor tuning, which is followed by a likewise commercial receiver as an intermediate-frequency amplifier, tuned to the in- /73 termediate frequency of 38.5 MHz. A low-frequency amplifier amplifies the frequency multiplex signal from the output of the demodulator, a signal corresponding to the signal at the output of the mixing amplifier in the on-board unit. This signal is then fed to the discriminator stages. These contain a band pass filter at the input, which passes through only the frequency band assigned to the discriminator. The actual discriminators then convert the frequency-modulated signal into a DC voltage, proportional to the voltage fed by the measuring device to the assigned subcarrier oscillator in the on-board unit. The output voltages delivered by the discriminators are about 3 V with the subcarrier oscillators driven to capacity. These voltages are then fed directly to the subsequent recording devices, e.g. a tape recorder and a UV printer. This record will immediately show whether the measuring process has been successful, or whether there were interferences (Quick Look). Further outputs can be e.g. hooked up directly to analyzing units.

The frequency multiplex signal can also be tapped at the output of the receiver before the input to the discriminators, and recorded with a tape recorder. This tape recording can then be played through the discriminators, yielding the same signal at the output as in the previous case with direct input.

In these measurements, subcarrier channels 9 through 14 were used in accordance with the so-called IRIG standard. The telemetry components (subcarrier oscillators, mixing amplifiers, transmitters, and subcarrier discriminators) were obtained from Vector, an American company.

Fig. 6 shows the detail of the electronic section of the model. The on-board telemetry unit is at the top of the picture.

Fig. 7 shows the telemetry receiver unit set up at the Institute for Flight Mechanics.

To facilitate analysis, the collimating-point signals of the /74 high-speed camera in the model, which films the inflation of the parachute, and the same signals of the camera which films the entire measuring process from the ground are recorded on the output of the UV recorder in the receiver unit. The collimating-point signals of the on-board camera are transmitted through the telemetry unit, and those of the ground camera through a coaxial cable. Since measurements can be taken with a kinotheodolite system to determine the trajectory, response pulses from this system are also marked on the record, thus providing a time scale for the analysis.

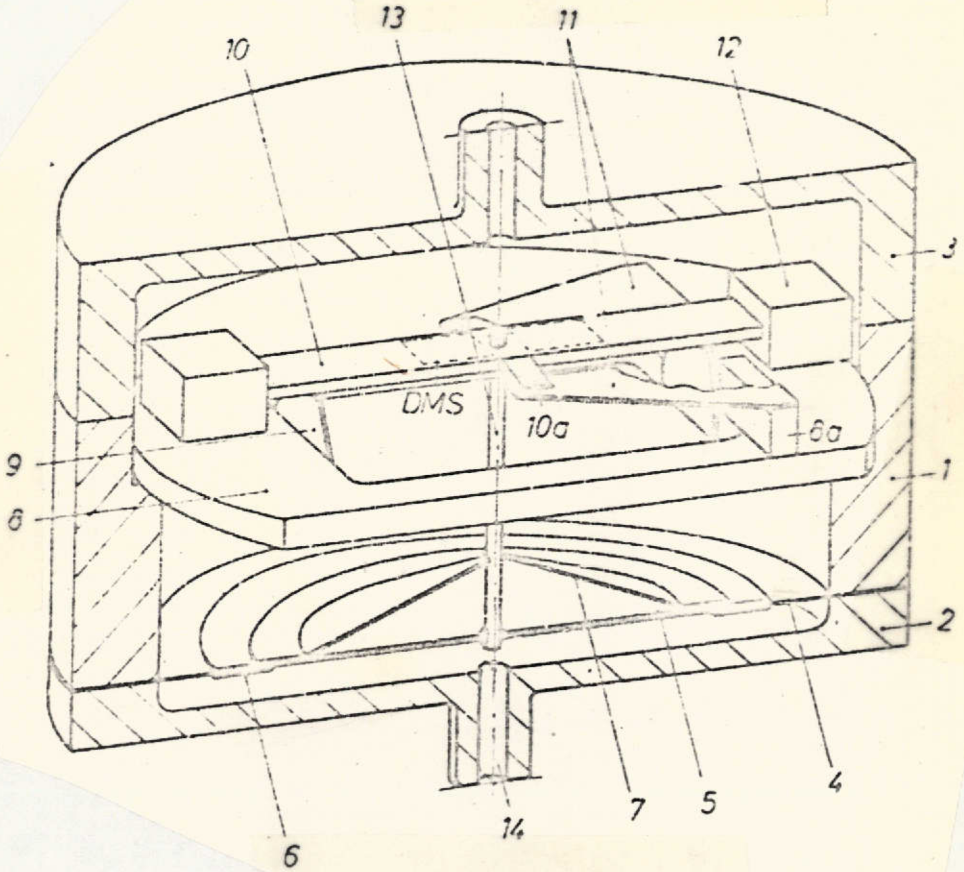

Fig. 1. Pressure sensor

DMS = strain gauge
1. Center section of housing
2. Top section of housing
3. Cover of housing
4. Plastic foil
5,6,7. Assembled aluminum diaphragm
8. Frame
9. Bending-element supports
10. Bending element
11. Braces against horizontal motions
12. Compensating weights
13. Wire connecting diagraph and bending element

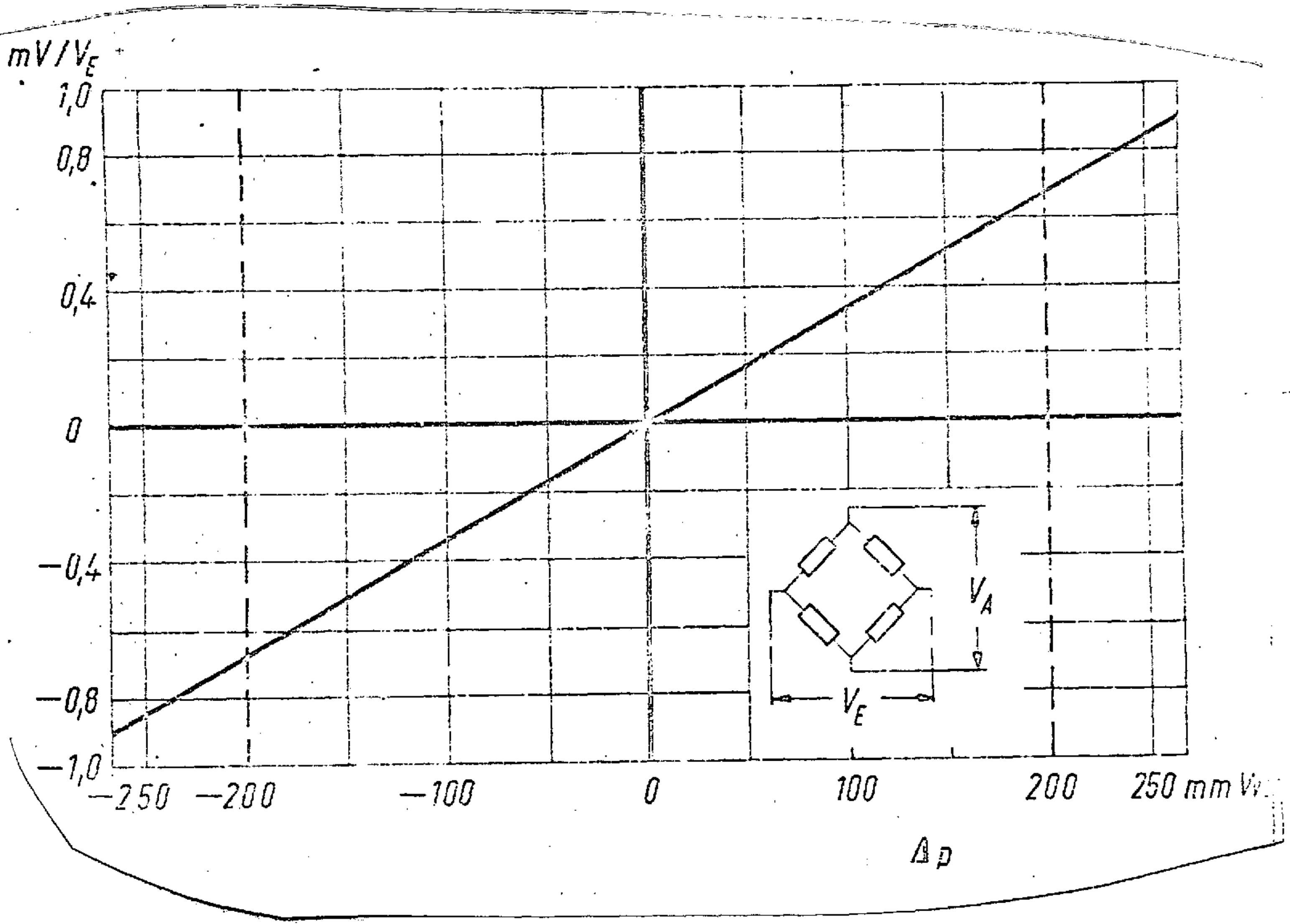

Fig. 2. Output voltage V_A in mV/V bridge input voltage V_E in relation to pressure difference ΔP.

[WS = H_2O (pressure)]

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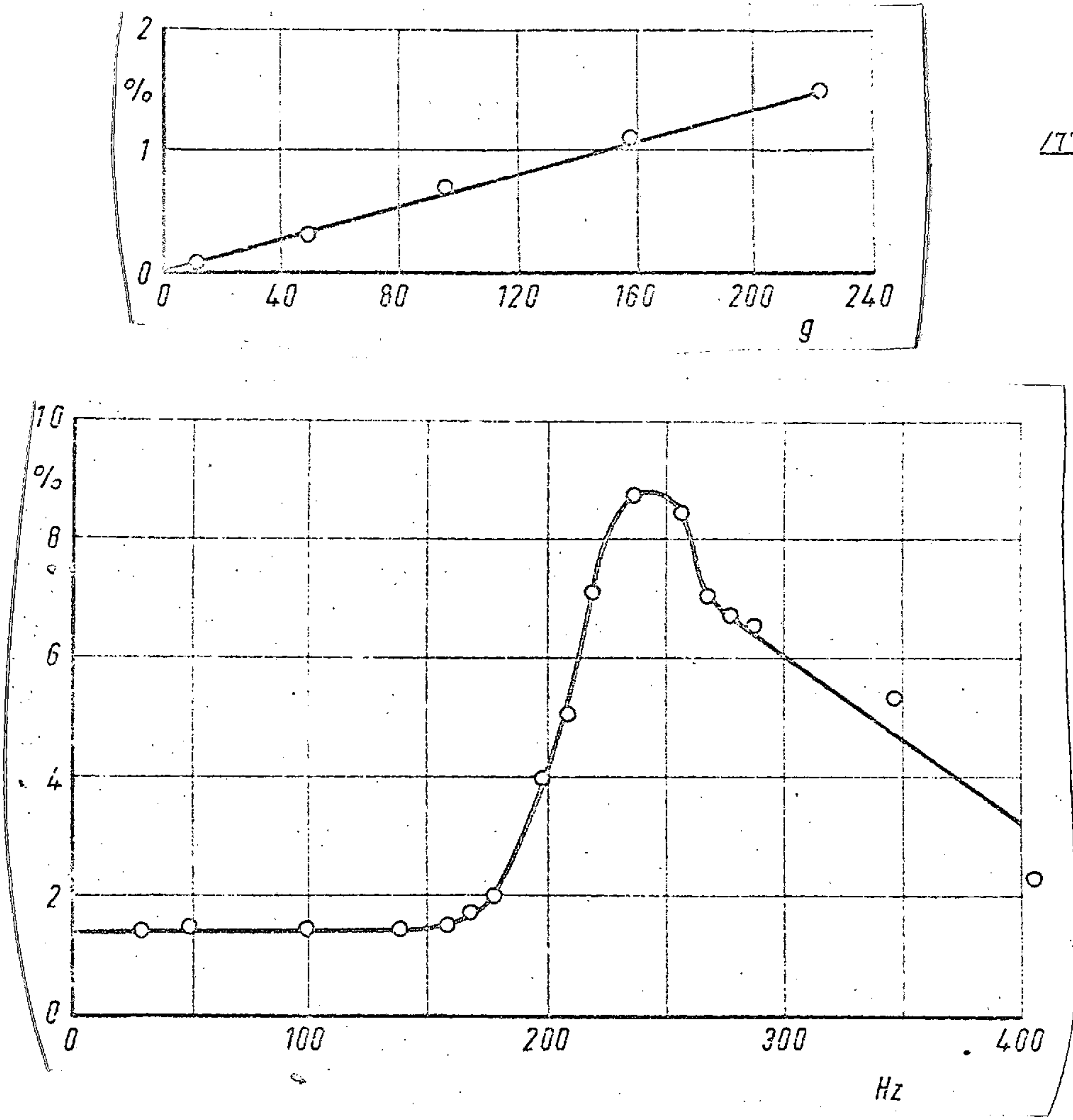

Fig. 3. Error curves.

Top: Error in percent of output signal at 200 mm H_2O plotted vs. acceleration in g normal to diaphragm.

Bottom: Error in percent of output signal at 200 mm H_2O plotted vs. frequency [Hz] of constant vibrational accleration.

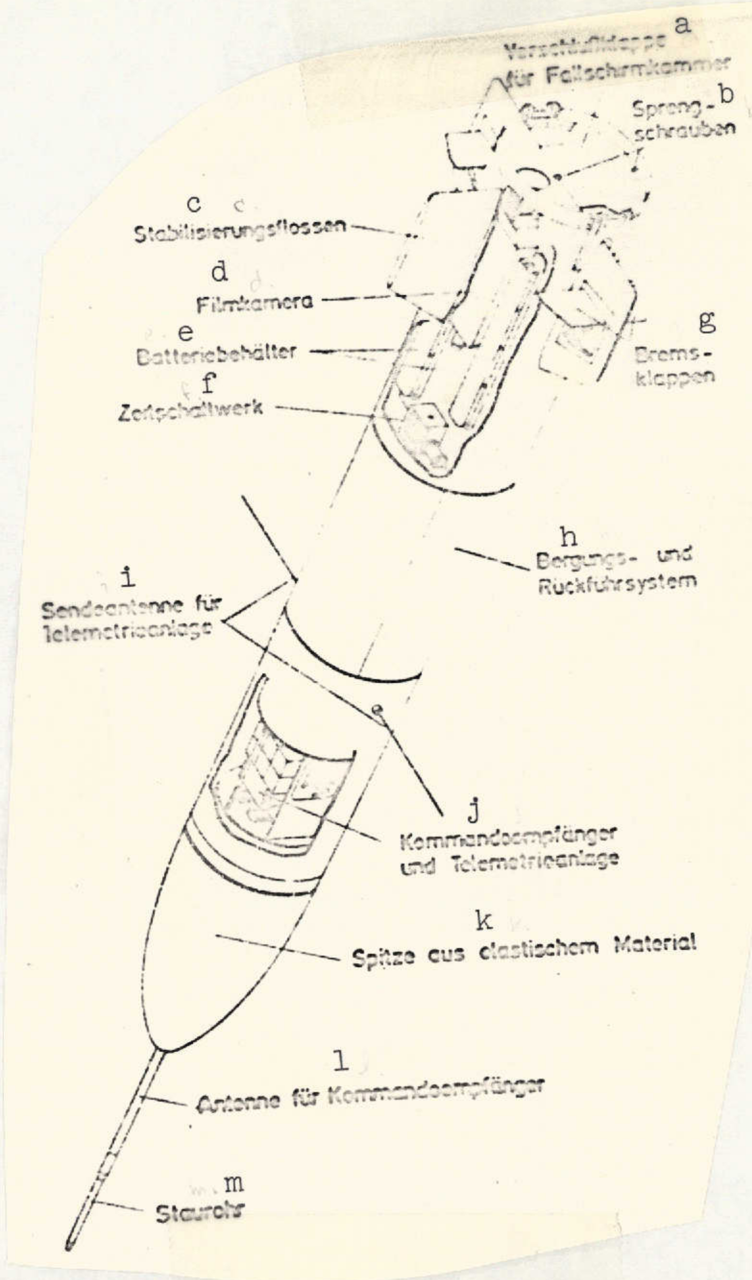

Fig. 4. Perspective drawing of model.

Key:

- a. Locking flap for parachute chamber
- b. Explosive ribbon
- c. Stabilizing fins
- d. Film camera
- e. Battery box
- f. Timer switch
- g. Deceleration flaps
- h. Recovery and return system
- i. Transmitting antenna for telemetry unit
- j. Command receiver and telemetry unit
- k. Nose of elastic material
- l. Antenna for command receiver
- m. Stagnation tube

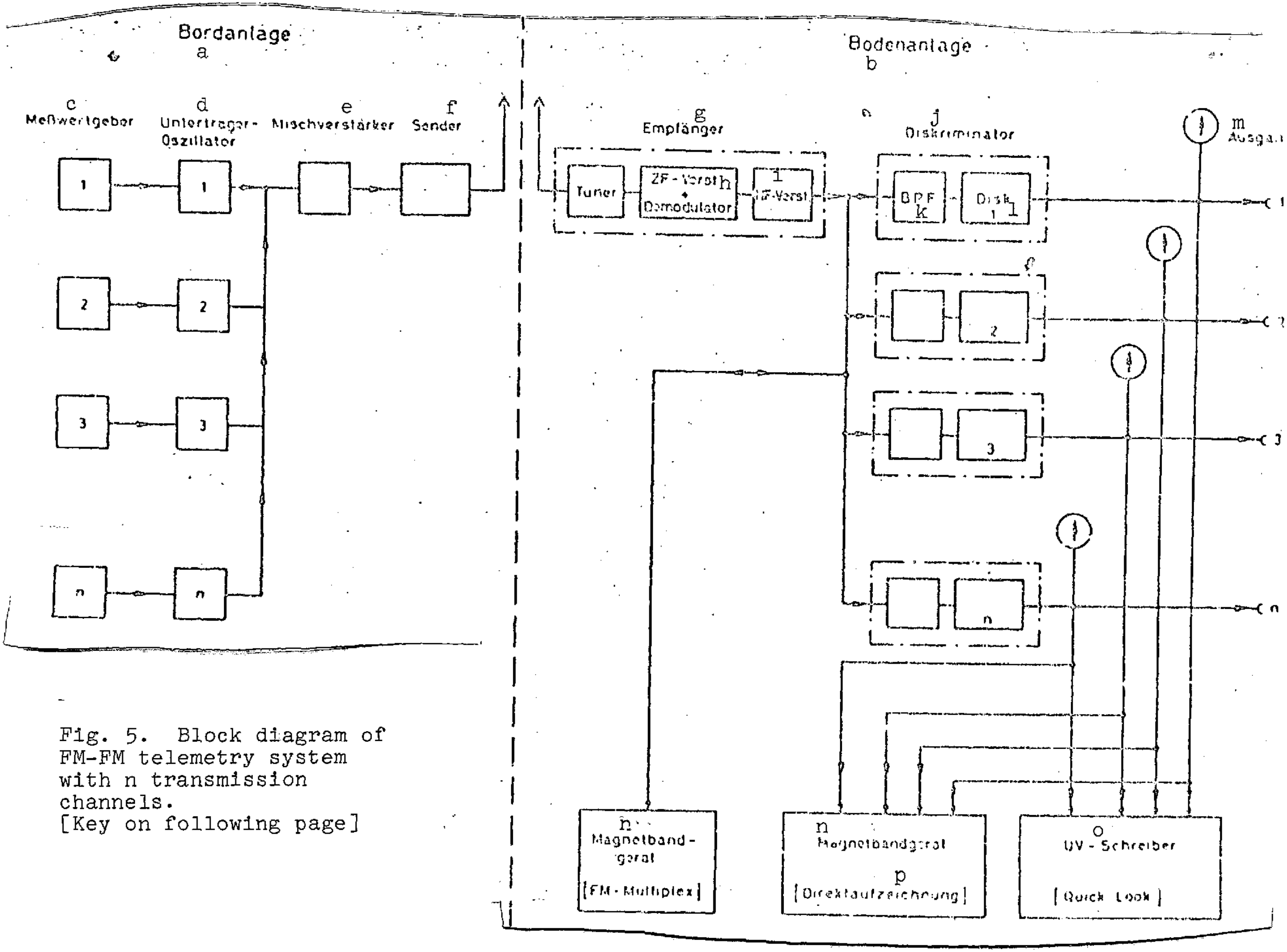

Fig. 5. Block diagram of FM-FM telemetry system with n transmission channels.
[Key on following page]

Key to Fig. 5.

a. On-board system
b. Ground system
c. Sensors
d. Subcarrier oscillators
e. Mixing amplifier
f. Transmitter
g. Receiver
h. Intermediate-frequency amplifier and demodulator
i. Low-frequency amplifier
j. Discriminator
k. Band pass filter
l. Discriminator
m. Output
n. Magnetic tape
o. UV recorder
p. Direct recording

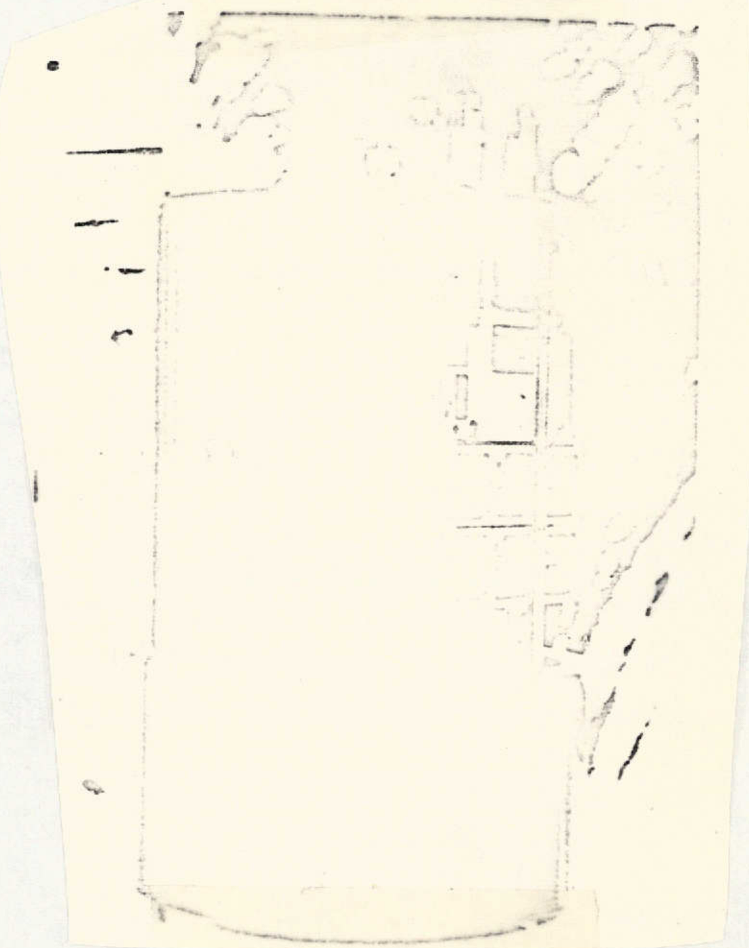

Fig. 6. On-board telemetry system.

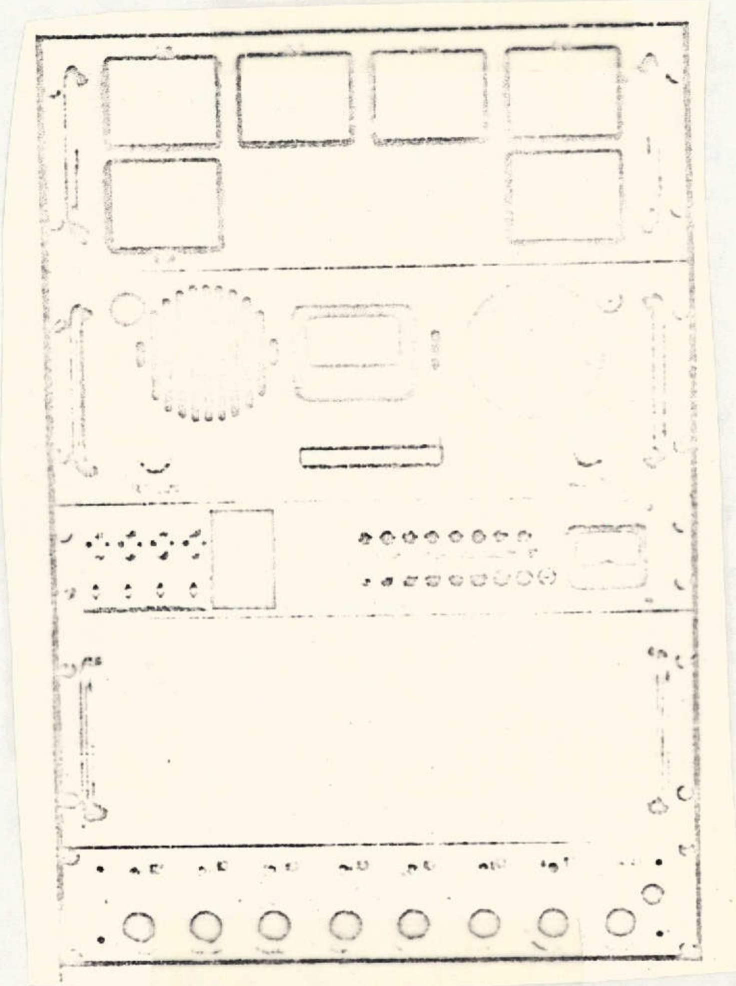

Fig. 7. Ground telemetry station. Display instruments, including receiver, in upper slide-in unit. Below receiver, slide-in unit for subcarrier discriminators. At bottom, output panel.

Exerpts from Discussion on Report of H.-J. Klewe /82

U. Schmidt: As a supplement to the remarks of Klewe, I would like to say a few words about pressure measurement in a parachute canopy. The result is depicted in Fig. 8. Four pressure sensors were attached to an extended-skirt parachute model, one near the top, two others between the edge and top, and the fourth at the edge. The measurements were taken in a wind tunnel with an airspeed of 30 m/sec. The diagram shows the records of the individual pressure sensors. The bottom curve represents the force. There was no opening shock peak, since before the experiment, the parachute model was deployed prior to electrical initiation. Consequently, only the inflation shock appears. The greatest pressure differences coincide fairly closely in time with the force peak. At the top of the picture is a 50 Hz time scale.

It is naturally difficult to generalize the results of such an experiment to conditions during a drop, since the parachute has a fixed suspension in the wind tunnel, so that its behavior corresponds to a parachute with an infinitely large suspended load, while the load in a drop has a relatively small mass, and the latter is strongly decelerated during the inflation phase. It has not yet been possible to apply a force curve measured in the wind tunnel to that of a drop.

Blenk: If you have measured pressure at various points on a parachute as a function of time, how are these measurements analyzed, and what conclusions can be drawn from them?

Schulz: The pressure distribution curves serve as a basis for /83 determining the stress distribution in the parachute in accordance with the analytical method of Prof. Heinrich and L.R. Jamison.

U. Schmidt: One needs not only the pressure distribution but also the curvature of the cloth at the points at which the pressure sensors are attached. However, it is difficult to analyze the canopy profile at these points precisely. The pressure sensors could, for example, be situated right in a fold.

Schulz: Are the records of which you have shown us a picture (Fig. 8) reproducible? Have you made many such records with identical results?

U. Schmidt: Yes!

Ahlborn: What is the accuracy of transmission?

Klewe: We try to keep the total error -- i.e. of the pressure sensors through the telemetry to the displays -- less than 5%.

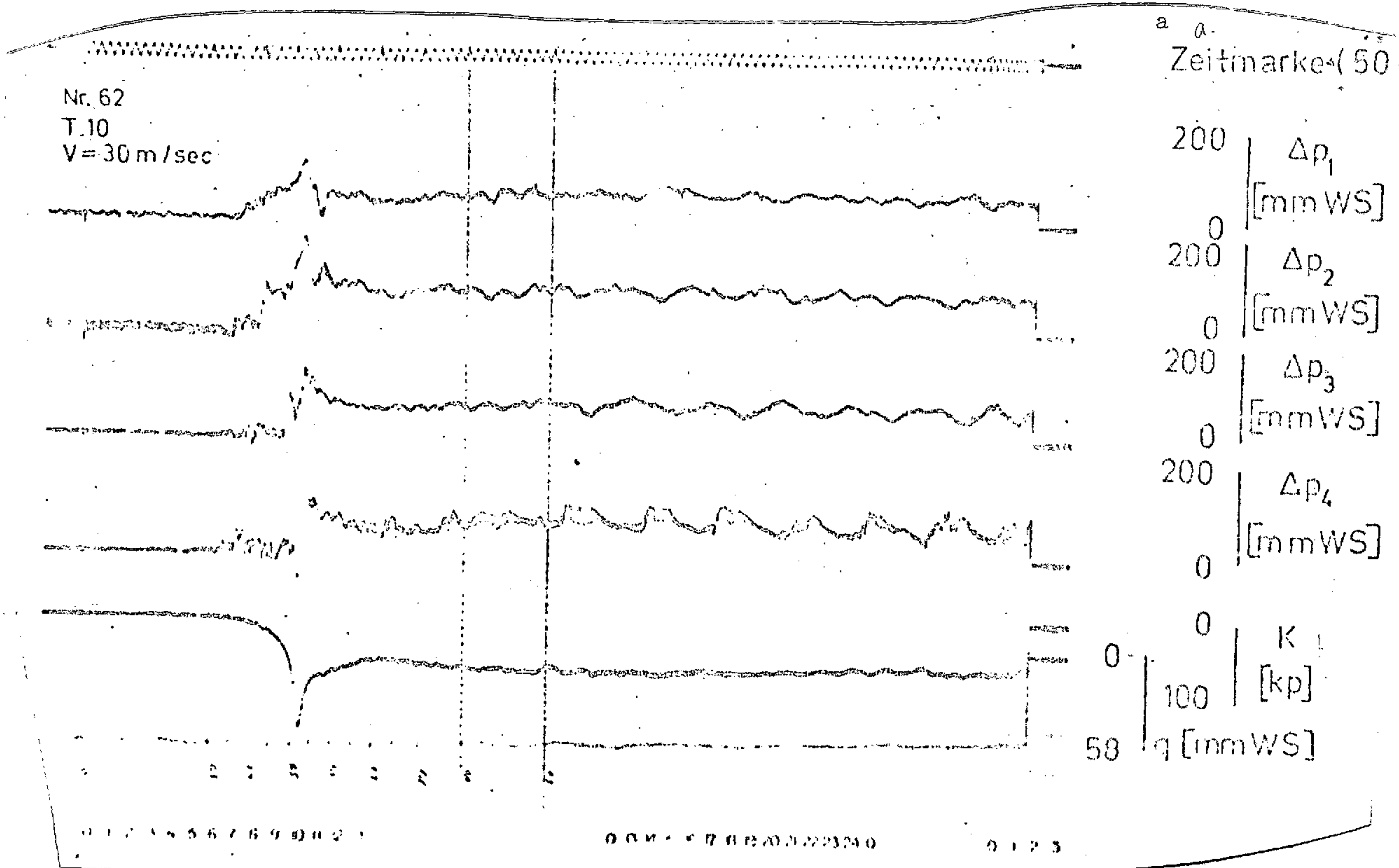

Fig. 8. Pressure difference p as a function of time (p_1 at the top, p_2 and p_3 between top and edge, and p_4 at the edge). Also, time variation of parachute force K and stagnation pressure q measured on a parachute canopy in the wind tunnel.

[WS = H_2O; kp = kg]

Key: a. Time scale

PARACHUTES AND RECOVERY SYSTEMS IN THE SUPERSONIC RANGE /85

(Helmut G. Heinrich, University of Minnesota, currently visiting at the German Research Laboratory for Aeronautics and Astronautics in Braunschweig)

1. Introduction

In the following I will attempt to give a survey report on the state of development of supersonic parachutes and of recovery technology with respect to practical applications. By a recovery system we generally mean one or more parachutes, arranged so that the aerodynamic drag area increases with time. This can be achieved by selecting a single large parachute, which is first deployed in a heavily reefed state; after a certain time, the first reef cord is cut and the projected area of the parachute is allowed to increase as much as permitted by a second reef cord. After another period of time, the second reef cord is also cut, and the parachute can open completely. In this way, one has a load on a parachute, the drag area of which changes in three stages, and one speaks of a three-stage recovery system. The same aerodynamic effect can be achieved by using three parachutes of different sizes, released one after the other until the load finally lands suspended from the last, fully opened parachute. Here too, one has a three-stage recovery system. However, it is also possible to combine the two recovery systems, e.g. putting together a parachute system consisting of one parachute which immediately opens all the way and a second parachute which is first deployed reefed, and then unreefed; again one obtains a three- /86
stage system.

Such multistage systems are generally necessary when the initial velocity at which the recovery procedure is to be initiated is very high and the actual landing speed is relatively small. In view of the velocity range to be spanned, the individual parachute stages must naturally be selected with great care, and this selection is particularly important when the initial velocity of the recovery process is supersonic. It is clear that the parachutes in the different stages must not only be designed with different strengths, but also be adapted aerodynamically to the particular velocity range. Furthermore, it is evident that parachutes intended for functioning at supersonic speeds must be designed differently with regard to shape and porosity than parachutes for subsonic speeds. Because of this requirement, special supersonic parachutes are needed for recovery systems beginning at supersonic speeds and ending at subsonic ones.

It is in the nature of a parachute recovery process that the speed first decreases very rapidly during the functional duration of a stage, then more slowly, and eventually approaches a constant equilibrium value. Parachute recovery systems can be imagined in which the initial velocity is in the supersonic range, but the velocity decrease is so fast that the supersonic phase is relatively short. In other parachute systems, in which the initial velocity is likewise supersonic, but which function at very great height or which carry very heavy suspended loads, the speed can remain supersonic throughout the functioning of the first stage. In the second stage, the initial velocity will probably be a lower supersonic speed, while the final velocity in this stage will be in the high or middle subsonic range. Hence, in design supersonic /87 recovery systems, allowance must be made not only for the maximum Mach number but also for the duration of the supersonic phase.

The practical result of these considerations is that for certain purposes, parachutes -- or quite generally aerodynamic deceleration devices -- are needed which will function over a relatively large range of Mach numbers, while for other applications, one can get along with parachutes or deceleration devices for which the initial Mach number is relatively small and which do not have to function very long in the supersonic range. For this reason, it seems useful to speak of genuine supersonic parachutes and of those representing to a certain extent transition types, which do not have to cope with speeds outside the low supersonic and high subsonic ranges.

Hence, a supersonic parachute is one which functions satisfactorily for an essentially unlimited period of time in flow e.g. between Mach numbers 5 and 1.1 or 0.9. By "for an unlimited period of time" is meant e.g. times on the order of 5 min. Longer durations in the flow may give rise to fatigue ruptures in the material under certain circumstances, and the parachute will be destroyed by mechanical causes, but not by aerodynamic processes. As an illustration, we should mention at this point that normally parachutes which function excellently at subsonic speeds flutter so violently at supersonic speeds that they are destroyed after just a few seconds and provide neither complete opening nor the desired aerodynamic deceleration force. The fluttering is generally induced by unsteady flow processes.

The idea of an unsteady and a steady supersonic flow can be seen in the Schlieren photographs in Figs. 1 and 2 [1]. In this case, the ribbon chute model (Fig. 1), if it were not made of sheet metal, would be destroyed in a very few seconds, while the model of a supersonic guide surface parachute made of nylon cloth (Fig. 2) can be exposed to supersonic flow for a practically arbitrary /88 period of time.

2. Types of Supersonic Parachutes

With regard to the potential uses of a parachute at a given Mach number and for a given duration, the following types of parachutes can be considered supersonic parachutes: Hyperflow parachutes, Parasonic parachutes, Supersonic Guide Surface parachutes.

Figs. 3 and 4 show schematically the Hyperflow and Supersonic Guide Surface parachutes [2, 1]. The Parasonic parachute can be viewed as a modification of the Hyperflow parachute, and the two are distinguished only in that the individual gores of the Parasonic parachute have curved side cords, while the gores of the Hyperflo parachute have straight edges and sharp corners. Rounding the gores of the Parasonic parachute certainly produces a shape freer of folds during opening, but does not produce any new aerodynamic effects as compared with the Hyperflo parachute.

The class of supersonic deceleration devices also includes the ballute, which is actually no longer a parachute, but an inflated balloon. A so-called Supersonic Ballute is shown schematically in Fig. 5 [3].

The types for moderate supersonic and high subsonic speeds are the so-called Equiflow and Hemisflo parachutes. Both types are modifications of known subsonic ribbon chutes, and differ from the latter only in the shape of the gore and in the amount of geometric porosity. The gore shapes are depicted schematically in Figs. 6 and 7 [2, 4].

3. Parachute Performance Data /89

The most difficult problem for supersonic and transonic parachutes is the formation of a stable bow wave in front of the entry opening and a steady pressure distribution on the canopy of the parachute. In order to obtain a steady bow wave and the prevent the flexible parachute canopy from fluttering, the porosity of the parachute canopy must be dimensioned so that the entire mass flow between the boundary flow lines is taken up by the parachute canopy, and can flow out through its porous rear wall. Sims discussed this principle in [5]; his analyses are depicted schematically in Fig. 8. A similar analysis was carried out in [1] for the Supersonic Guide Surface Parachute, the principle of which is depicted schematically in Fig. 9. The same considerations should apply to the Parasonic, Equiflo and Hemisflo parachutes. By shape, the ballutes are spheres inflated by stagnation pressure and there is no mass flow through them. Aerodynamically, the ballutes are therefore much simpler than parachutes.

Schlieren pictures of the flow pattern around the Hyperflo parachute are found in [5], and the schlieren picture of the Supersonic Guide Surface Parachute was already shown in Fig. 2. Ballutes have schlieren pictures very similar to those of the Supersonic Guide Surface Parachute (see Figs. 10, 11, and 12 in [6]). In comparing these three pictures, the influence of the wake of the leading object on the shape of the bow wave of the ballute is very evident. The flow patterns of the Equiflo and Hemisflo parachutes are similar to those of the Hyperflo parachutes, and are likewise distinguished by a relatively steady bowwave.

Even though these flow patterns do illustrate interesting details of aerodynamics for the devices concerned, the drag data for the various parachutes are still of great practical significance. We will now exhibit a few characteristic drag figures.

The drag coefficient of the Hyperflo parachute is essentially that depicted in Figs. 13 and 14. We should remark that these drag figures refer to the projected area in accordance with the design diameter and not to the total surface of the parachute canopy as is the usual case in parachute construction. The drag coefficients of Supersonic Guide Surface Parachutes are somewhat greater than those of the Hyperflo parachutes and are shown in Fig. 15. These drag data also refer to the projected area of the parachute canopy. /90

Drag coefficients of the ballute, where known, are given in [6], and are shown in Fig. 16. The author of this publication remarked that these were average values, obtained with a ballute in the wake of a "relatively slender leading object." These drag numbers also refer to the projected area of the body; they are essentially of the same order of magnitude as those of the Hyperflo parachutes. The position of the ballute relative to the rear side of the leading object appears to have a particularly strong influence on the drag coefficients of the ballute, as can be seen from Figs. 17 and 18. These pictures were derived from the illustrations of Jaremenko [6].

For the Equiflo and Hemisflo parachutes, the drag data are given in the USAF Parachute Handbook [4], the values referring to the total surface of the parachute canopy. In this representation, the drag coefficients are on the order of $c_{D0} = 0.25$, and vary relatively little with Mach number within their general range of function.

4. Further Problems in Supersonic Deceleration Devices

The steadiness of the flow patterns and the aerodynamic drag coefficients are just two of the general problems associated with the development of supersonic deceleration devices. The aerodynamic heat load and the general stress calculation are the two other large problem areas. So far, the wind tunnel experiments have generally employed relatively low air densities, so that thermodynamic difficulties were hardly ever observed. However, in experiments on recovering devices from supersonic speeds, it has /91 been repeatedly observed that parachutes made of the well-known synthetic fibers Nylon or Dacron burned up completely or melted, so that only the cords and the particularly thick components of the flexible canopy could be found after the landing. For this reason, serious efforts are underway to develop textiles with melting points higher than the customary materials Nylon, Perlon, and Dacron. A new item in the textile field is the so-called Nomax, which has a markedly higher melting point. Fibers and yarns can be prepared from it, and it retains its strength under conditions at which Nylon or Dacron would already have failed completely.

Another, more radical development is the fabrication of deceleration devices of metal fabrics, such as stainless steel. Attempts are being made to build such deceleration devices from stainless steel gauze, particularly in connection with development for the ballute. The fundamental difficulty in this method of construction is, however, the interconnection of the individual gores, and no satisfactory solution has yet been found. In [9], fabrics and fabric connections used in the construction of ballutes from metal fabric are described. In essence, the designers have attempted to build these deceleration systems in the usual way from gores, connected by point welds, and made airtight by special strips. This procedure naturally results in a construction in which the connecting seams are relatively stiff and hard to pack. The efficiency of such welded seams is also generally less than that of well-made seams in conventional textiles. Recall /92
that in textile parachute construction, seam connections are considered just satisfactory if they have an efficiency of 75%, and not viewed as very good until 85%. The efficiency of point welded seams in metal fabric should be much lower, quite apart from the complications anticipated in packing because of the stiff seams.

The strength of supersonic parachutes and ballutes does not constitute any special problem, as long as the flow patterns remain steady. For steady flow patterns, the pressure distributions are known, and the supersonic parachutes should be accessible to known computational techniques, such as those given in [10].

However, if there are high-frequency material vibrations generated and maintained by uncontrolled vortex separation and unsteady compression shock waves and the like, destruction of the device must be anticipated after a very short time, due to material fatigue.

The reduction in material strength due to the heating of the material, stemming from the compression heat, is a problem which is well known, but which has not been satisfactorily solved at this time.

5. Summary

Aerodynamic deceleration systems are required for recovery techniques for flying objects of diverse types, particularly space capsules. They must be very light and when packed, must fit into a very small space. When inflated, the devices must generate an aerodynamic drag which is as large as possible. So-called ballutes have been proposed for use at subsonic speeds as well as at relatively high supersonic speeds. There are indications that the current state of the art permits construction of /93
ballutes which can function satisfactorily at Mach numbers up to 10. Parachute types of the so-called Hyperflo and Supersonic Guide Surface Parachute classes have given promising results in the wind tunnel at Mach numbers up to 5. In practical tests and real recovery techniques, satisfactory operation has been demonstrated up to Mach 3. There are no known tests at higher speeds. The Equiflo and Hemisflo parachutes can be considered function-ready at low supersonic and high subsonic speeds. These parachutes have generally mastered the range from Mach 1.5 down into the incompressible flow range, where conventional subsonic parachutes also function.

The conditions resulting from the aerodynamic heating of the parachute material have not yet found any general and satisfactory solution, but there are indications that metallic fabrics will be available for future development.

Symbols

C_{Do}	Drag coefficient, relative to nominal area
C_{Dp}	Drag coefficient, relative to projected area
d	Diameter of leading object
D_o	Nominal diameter
D_i	Intake diameter
H	Distance of cone vertex from inlet plane of Supersonic Guide Surface Parachute
l	Distance between trailing end of leading object and tip of cone of Supersonic Guide Surface Parachute or of ballute
$\dot{m}$	Mass flux
$\dot{m}_\infty$	Mass flux in freestream
Ma	Mach number
Ma_∞	Mach number in freestream
α	Wake angle
Θ	Cone angle

Fig. 1. Unsteady flow pattern around rigid ribbon chute model at Mach 3 [1].

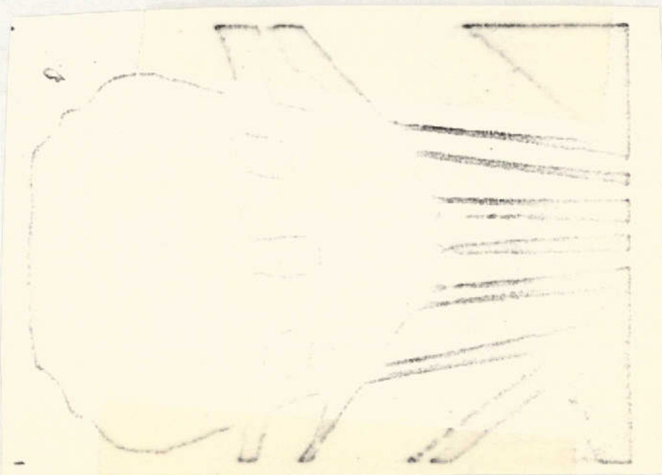

Fig. 2. Steady flow pattern around flexible model of a Supersonic Guide Surface Parachute [1].

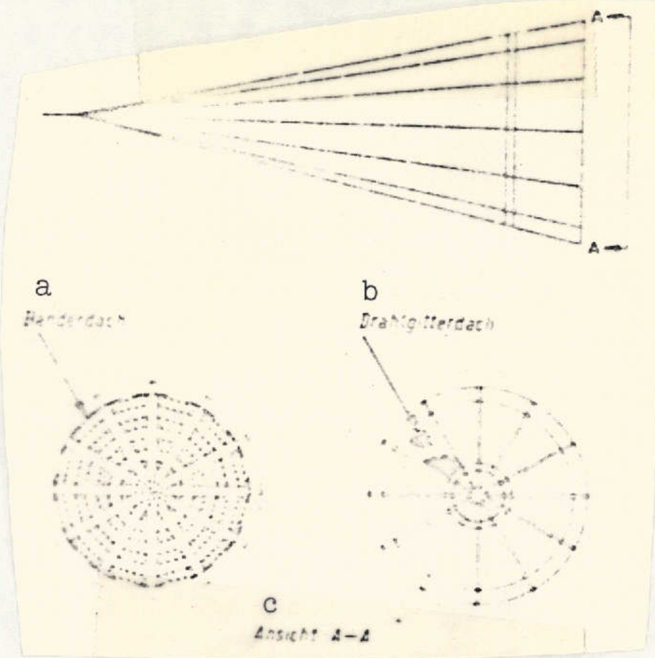

Fig. 3. Profile and rear side of Hyperflo parachaute [2].

Key: a. Ribbon roof; b. Wire grate roof; c. View

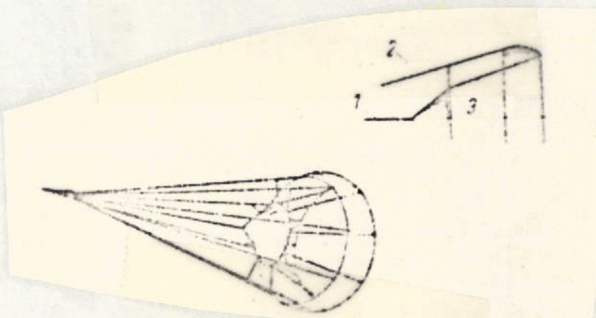

Fig. 4. Schematic of Supersonic Guide Surface Parachute [1].
1 = cord from tip of cone to intersection of cords
2 = eight lines from leading edge of canopy to intersection of cords
3 = eight lines from base of cone to trailing edge of canopy

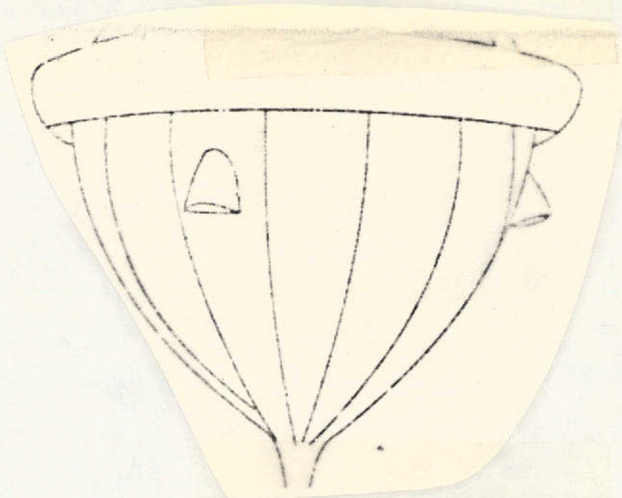

Fig. 5. Supersonic Ballute [3].

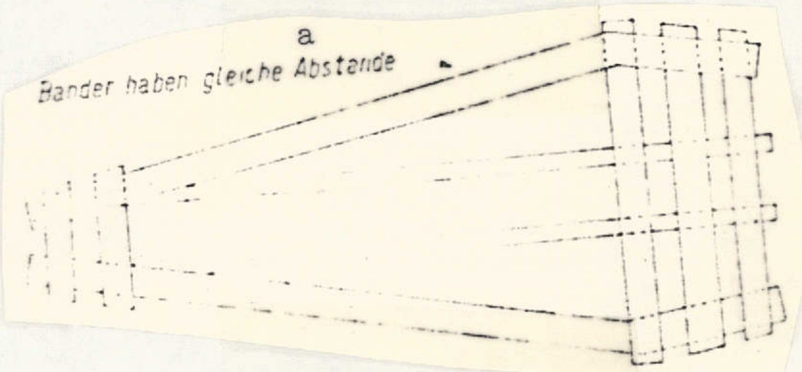

Fig. 6. Gore frame of Equiflo parachute [2].
Key: a. Ribbons have equal distances

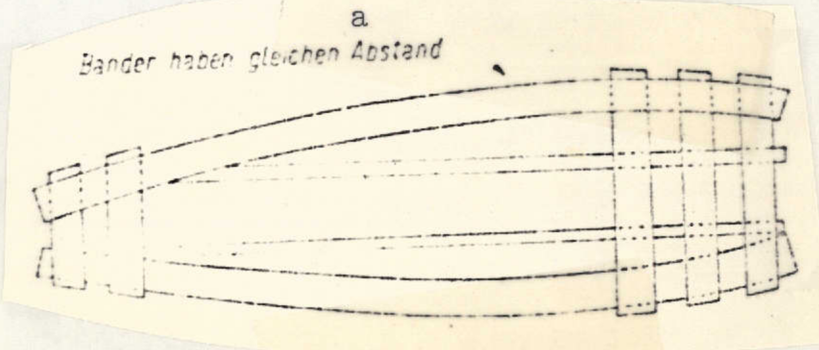

Fig. 7. Gore frame of Hemisflo parachute [4].
Key: a. Ribbons have equal distances

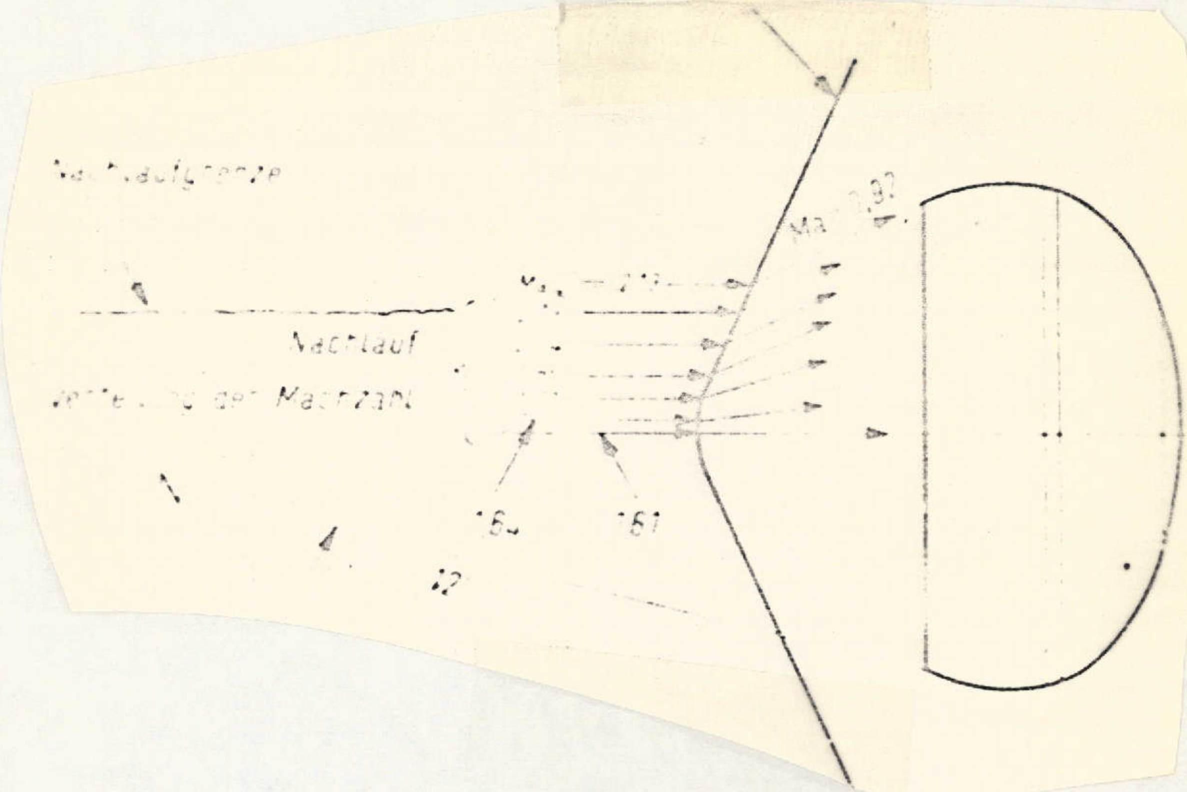

Fig. 8. Flow pattern and shape of bow waves of Hyperflo parachute in wake of a leading object [5].

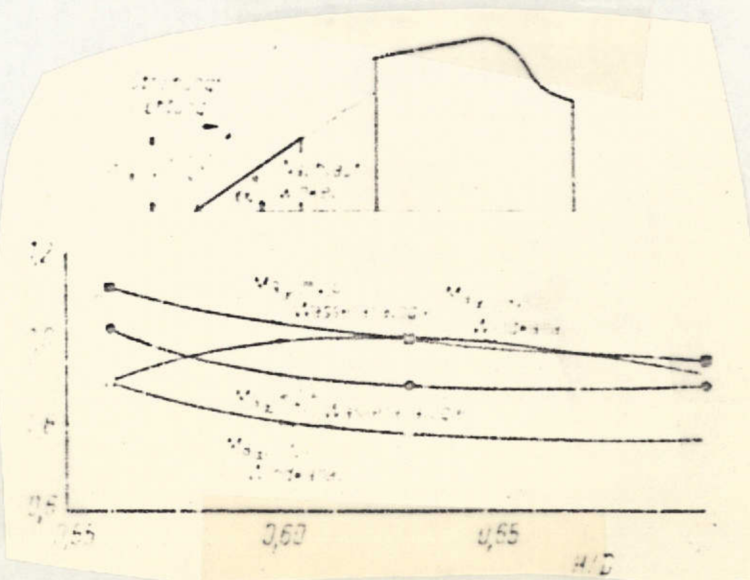

Fig. 9. Schematic of mass flux of a Supersonic Guide Surface parachute at a cone angle of $\Theta = 34°$ equal to the wake angle α [1].

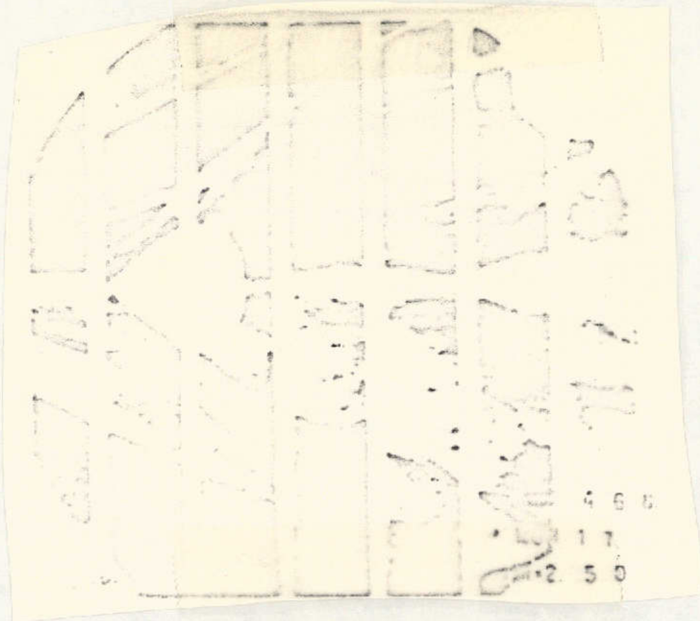

Fig. 10. Schlieren photograph of a ballute [illegible].

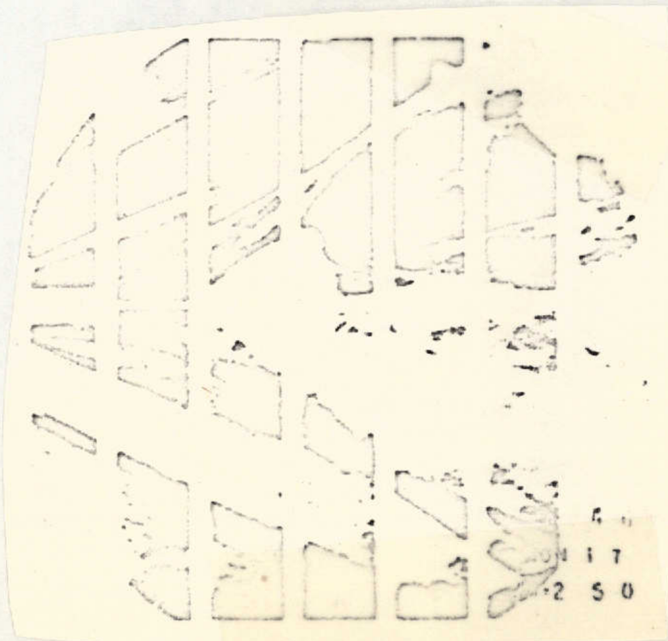

Fig. 11. Flow pattern of a ballute [illegible].

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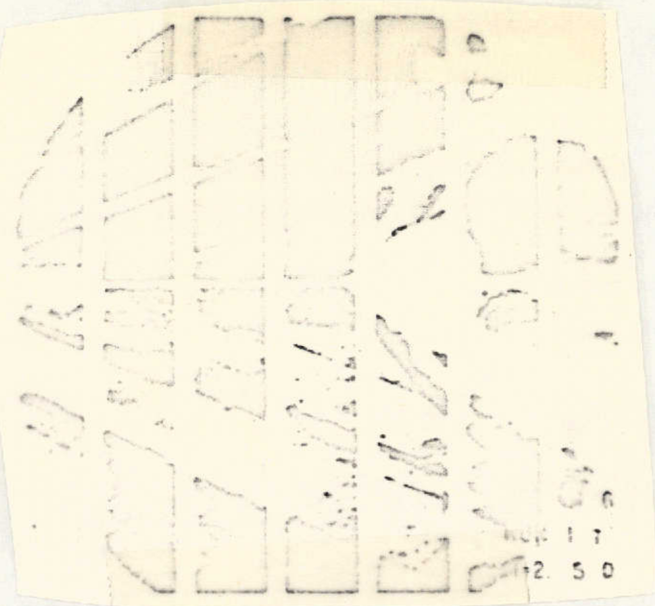

Fig. 12. Flow pattern of a ballute [illegible].

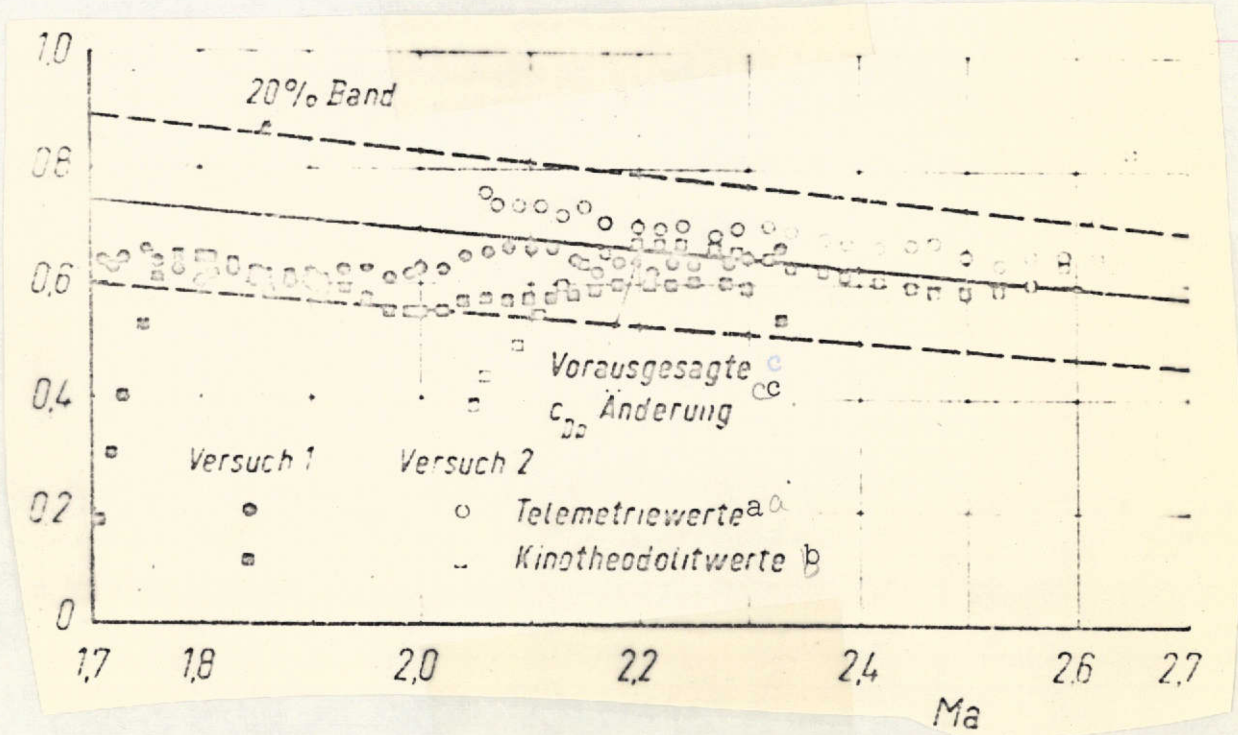

Fig. 13. Drag coefficients of Hyperflo parachute as determined by freefall tests [7].

Key: a. Telemetry values
b. Kinotheodolite values
c. Predicted change in c_{Do}
Versuch = test

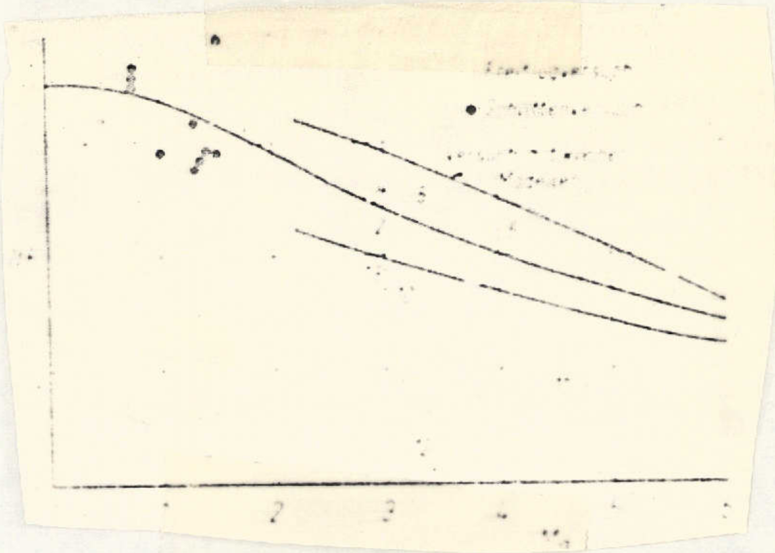

Fig. 14. Drag coefficient of Hyperflo parachute [8].

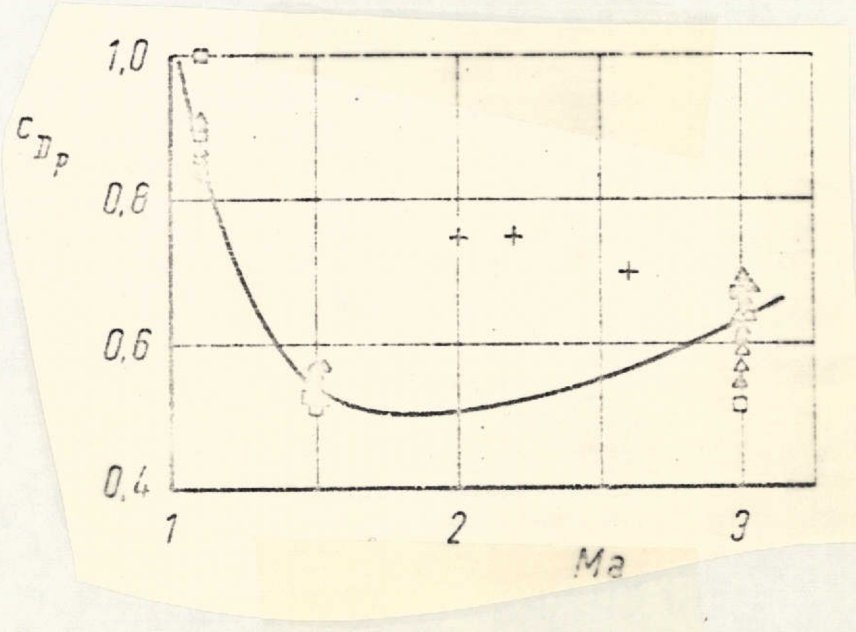

Fig. 15. Drag coefficients C_{Dp} of Supersonic Guide Surface Parachute [1].

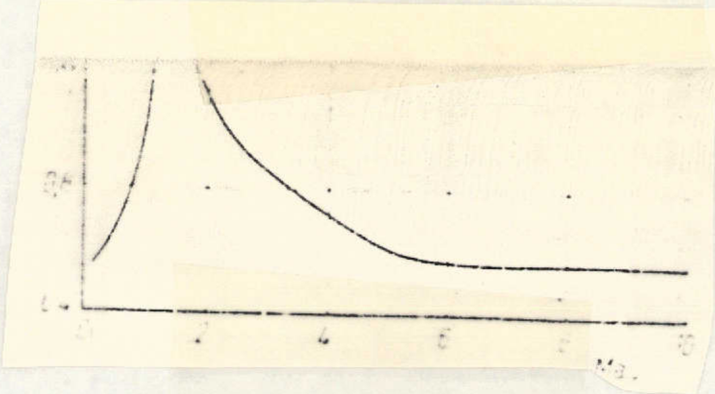

Fig. 16. Drag coefficient of ballute [6].

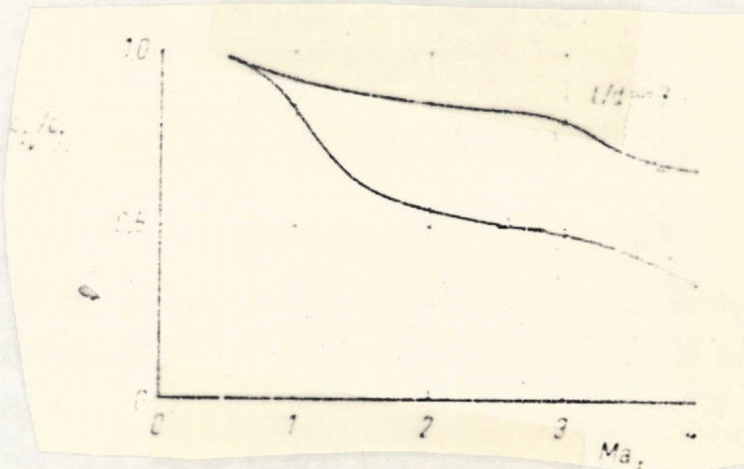

Fig. 17. Drag coefficients of ballute in relation to position in wake [6].

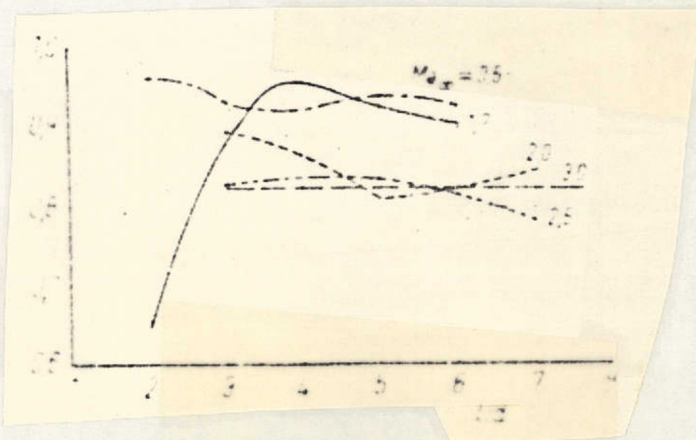

Fig. 18. Drag coefficient of ballute in relation to position and Mach number [6].

REFERENCES

1. Heinrich, H.G., "Aerodynamic principles of the supersonic surface parachute," WGDR-Jahrbuch 1964, 278-289. /94

2. Sims, L.W., "Study of parachute performance and design parameters of high dynamic pressure operation," USAF Technical Report, FDL-TDR 64-66, May 1964.

3. Nebiker, F.R. and Ross, R.S., "Ballute -- a contemporary stabilizing and decelerating device with a future," Goodyear Aerospace Coorporation GFR 12289, July 6, 1975, presented at University of Minnesota, Lectures on Final Phase Aerodynamic Deceleration, July 6-16, 1965.

4. "Performance of and design for deployable aerodynamic decelerators," USAF Technical Report No. ASD-TDR-61-579, December 1963.

5. Sims, L.W., "Analytical and experimental investigation of supersonic parachute phenomena," USAF Technical Report ASD-TDR-62-844, November 1962.

6. Jaremenko, I.M., "Aerodynamic characteristics of the ballute in the 0.1-10 Mach number speed range," AIAA Paper No. 67-228, New York, January 23-28, 1967.

7. Turner, H. and McMullen, J.C., "Feasibility of parachute operation at high Mach numbers and dynamic pressures," AIAA Paper 66-24, New York, January 24-26, 1966.

8. Sims, L.W., "Concept, aerodynamics and design details of Hyperflo parachutes -- a summary," presented at University of Minnesota, Lectures on Final Phase Aerodynamic Deceleration, July 6-16, 1965.

9. Alexander, W.C., "Investigation to determine the feasibility of using inflatable balloon type drag devices for recovery applications in the transonic, supersonic and hypersonic flight regime," USAF Technical Report ASD-TDR-62-702, Part II, December 1962. /95

10. Heinrich, H.G. and Jamison, L.R., "Parachute stress analysis during inflation and at steady state," Journal of Aircraft 3(1) (Jan.-Feb. 1966).

Beer: I would like to bring up the thermodynamic side. It will certainly not be just the adiabatic compression which results in temperature rises, but also the conversion of kinetic energy into heat in the boundary layer, the so-called aerodynamic heating. A measure of this effect is the eigen-temperature, and it is known that temperature differences of about 200-300° occur at Mach numbers around 2.5, while the temperature differences are as large as 1000° at Mach numbers around 5. Might it not be that at still higher Mach numbers, wire fabrics will not be adequate at all? Are there any known concrete methods of investigation or solution techniques, e.g. ablation cooling, by which to approach this problem?

Heinrich: Fundamentally, the initial effort is being directed at obtaining a refractory fiber. The development of metal cloth is just one possibility. Efforts are also underway aimed at using sintered materials, based on ceramics. The use of fiberglass-reinforced synthetic materials has failed so far, because corresponding cloths cannot be joined well. A parachute sewn together with fiberglass usually breaks along the seams. Surface cooling is being worked on; for example, attempts have been made to attach very small spheres of plastic material, filled with a cooling liquid, to the cloth. These spheres burst because of the heat, the liquid evaporates, and this cools the parachute for a while. This method is being studied by Stanford University in San Francisco and by G.D. Schjeldahl Co. in Northfield near Minneapolis. There are certainly many other possibilities as well for cooling.

Beer: Have temperature measurements been made on an existing /106 parachute?

Heinrich: I have seen parachute canopies covered with temperature-sensitive dyes, and inferences have been drawn about the temperature distribution from the color. Essentially, however, Prof. Ernst Bekert is the one interest in these thermodynamic problems; my group is more worried about the aerodynamics.

Azmeh: What do you think of paragliders as a recovery system?

Heinrich: North American Aviation worked on them for a long time, wishing to develop a paraglider -- a completely flexible structure -- for the recovery of the Gemini capsule. This was given up as fruitless. New efforts have been initiated under the auspices of NASA. Such a development may be possible. I would not like to give a conclusive verdict.

Schulz: Why is it necessary that the deceleration at hypersonic Mach numbers up to 15 be provided by drag-inducing objects and not by braking rockets?

Heinrich: Performance calculations appear to show that if a parachute can be used for deceleration, less weight is needed than with braking rockets. Since parachutes have been developed rather far up to Mach number 4 or 5, it is hoped that e.g. the last landing phase on Mars, which begins at Mach number 5, can be carried out with parachutes. If parachutes were available for Mach number 10, they would probably be used in that range as well.

Blenk: I am really quite astonished that there are hopes of using parachutes on Mars, since the density of the atmosphere is after all very low. /107

Heinrich: It is true that the density of the Martian atmosphere is low, but the gravity is only 38% of that of the Earth. The projected weight of the Mars capsule is about 850 lbs, and it should impact the surface of Mars at about 100 ft/sec, hanging from a parachute 80 ft in diameter. The impact will be softened by shock-absorbing material.

Ahlborn: Is the ballute not far superior to parachutes in the supersonic range? Even in regard to thermal loads, I believe it is easier to apply an insulating layer to the ballute than to a parachute.

Heinrich: On the basis of equal drag areas, a parachute for Mach number 5 is probably lighter and cheaper than a ballute for the same Mach number. The development of heat-resistant material is just a question of time and should be equally difficult for ballutes and parachutes.

Beer: How long does a parachute function at Mach number 5?

Heinrich: Supersonic parachutes have functioned for practically unlimited times in the wind tunnel.

Beer: Does this really mean 5 min?

Heinrich: If they work for 5 min, then they do it for 30 min as well. A supersonic parachute must not flutter, either for 5 min or for 30 min.

Saliaris: Are there any special parachutes for the recovery of meteorological systems? I refer to the difficulties which occur when a parachute is to be opened at a relatively small velocity and at great altitudes, where the pressure and density of the air are very small. /108

Heinrich: I know one method, which was developed at G.T. Schjeldahl Co. This was a parachute the lower edge of which was double-walled, and which, when it opens, is similar to a wide-ribbon parachute. In the double-walled section of the parachute are capsules containing specific salts. When the parachute is deployed, the capsules burst and the salts evaporate because of the low air pressure. The lower edge of the parachute forms an inflated ring. G.T. Schjeldahl also used this method for the satellites Echo 1 and Echo 2. There are still other systems, but this is one of the simplest, and such parachutes have been tested with good success in preparation for Mars landings.